THE ENERGY BALANCE EXPERIMENT EBEX-2000

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Table 1: Recent energy balance observations.

Experiment	Residual (%)	Surface
KUREX-98	23	various
FIFE-89	10	grassland
Vancouver I90	17	16m forest
TARTEX-90	33	barley/bare soil
KUREX-91	33	various
LINEX-96/2	20	medium grass
LINEX-97/1	32	short grass
LITFASS-98	37	bare soil

1 INTRODUCTION

The primary objective of the Energy Balance EXperiment (EBEX) was to determine why micrometeorological measurements of the terms of this basic physical quantity (sensible H and latent heat flux LE, net radiation R_{net} , soil heat flux and storage G) often cannot achieve closure. Table 1 shows the imbalance for a few experiments. It is quite common for experimental data sets to have H+LE+G be only 70-90% R_{net} . This error is much larger than is usually expected for the measurements of any of the individual terms.

EBEX was the direct result of a European Geophysical Society workshop (Foken and Oncley, 1995), which listed both instrumentation and fundamental problems in closing the energy budget. EBEX addressed these problems by:

- Measuring all terms of the energy budget directly at comparable scales. In particular, deploying enough sensors to create an average of each term over one half square mile (1.6 km by 0.8 km), which encompassed several flux "footprints".
- Performing side-by-side intercomparisons of instruments from different manufacturers.
- Comparing processing methods of different research groups, including filtering and flow distortion corrections in the eddy-correlation measurements, using a reference data set.

In addition, temperature and wind profiles were measured at 3 locations to provide information about the site homogeneity, including horizontal advection.

EBEX expended considerable effort sampling all the terms on the same spatial scale, however it was not expected that this is the primary source of the imbalance observed in the past, since H+LE+G could be either larger or smaller than R_{net} . More likely causes are inadequate averaging in time (which would lose low-frequency contributions to H and LE), inadequate data processing, or insufficient characterization of G.

2 EXPERIMENT DESCRIPTION

EBEX wanted to study a surface for which energy balance closure has been difficult to obtain, but is relatively easy to instrument. A closed canopy with high evapotranspiration (typical of many forest sites) is one such case. We selected a flood irrigated cotton field in the San Joaquin Valley of California since the typically

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cloud-free skies resulted in quite high evapotranspiration, with maximum values of 600 W m⁻². The overall topography was quite flat with the slope of 0.1 degree.

Most flux measurements were made 4 m above the canopy and thus had a fetch (at least in unstable conditions) of about 400m. The layout of the tower sites (Figure 1) with tower spacing of 200 m was chosen to have this footprint totally within the cotton field and to have overlapping footprints from adjacent towers to identify any sections of the field with significantly different fluxes.

All sites had measurements of momentum, sensible, and latent heat flux at one or more heights, soil temperature, moisture, and heat flux, net and upwelling visible radiation. Most sites (1-6, 8) also had upwelling infrared radiation. Sites 7, 8, and 9 also measure wind, temperature, and humidity profiles at 6 or more levels and downwelling visible and infrared radiation. Canopy heating was measured near sites 9 and 10. For a brief period, soil and canopy heating was measured at 4 locations along a row just north of site 7 and a row north of site 1.

Sites 7, 8, and 9 all had redundant flux measurements using different sensors so that the results may be applied to other studies. For example, three-dimensional sonic anemometers from Applied Technologies, Inc., Campbell Scientific, Gill Research, Kaijo-Denki, and Metek were deployed. For the first 10 days of the experiment, all of these sensors were deployed side-by-side for a flux instrument intercomparison. Although most of the data from these sensors were acquired by NCAR's Integrated Surface Flux Facility (ISFF), each group also collected their own data so that data processing methods may be compared.

The field was flood irrigated over a period of several days (working North to South) twice during the observation period as indicated in Figure 2. With this schedule, about half of the time the soil moisture was not uniform across the field, though the fluxes were not dramatically different.

Winds were quite steady from the NNW at upper levels in this location, as shown in Figure 3. Near the surface, winds from the NE also occur at night.

3 RESULTS

Analysis of the EBEX dataset is multifaceted, so a complete summary is impossible here. A few highlights are described.

One goal of EBEX was to test whether the data analysis software used by the various research groups worked properly. For this test, each group analyzed two days of data from one sonic anemomemeter and krypton hygrometer. Since each group started with



Figure 1: Infraed imagery of the 1600x800 m EBEX field site, with the tower site locations (1-10) indicated. The canopy was coolest near site 4, but still was completely closed near sites 1-5. Sites 9 and 10 were in a less productive part of the field, where the canopy never completely closed. North is up in this image.



Figure 2: Irrigation schedule during EBEX-2000.



Figure 3: Wind directions and speeds measured by a minisodar at 100 m and by a sonic anemometer at 6 m.

identical time series, we expected the computed fluxes to be quite similar. Differences of up to 2% were seen in the momentum flux, 5% in the sensible heat flux, and 15% in the latent heat flux (see Figure 4). About 10% of the difference in latent heat flux was due to one group not correcting for the spatial displacement of about 0.3 m between the two instruments. The next biggest difference probably is whether each group applied linear detrending to the time series. For this data set, the method of anemometer coordinate rotation, and implementation of the oxygen, Webb and other corrections appears to have only a small effect on the computed fluxes.

Another test during EBEX was comparison of sensors from different manufacturers. As an example, downwelling longwave-radiation measured by Epply PIRs and Kipp and Zonen CNR1s are shown in Figure 5. Based on this and similar analyses of the shortwave



Figure 4: Comparison of half-hour values of the latent heat flux computed by the various research groups on the same data set. Differences are mostly due to the choices of data correction algorithms.



Figure 5: Downwelling long-wave radiation measured by the Bayreuth CNR1 (circles), Bayreuth PIR (squares), and Basel CNR1 (triangles) relative to the NCAR PIR. Neither PIR has been corrected for shortwave radiation. Such a correction would move the midday values up about 15 W m^{-2} .

and net radiometers, 4-component radiation measured by Kipp and Zonen radiometers was chosen to be the standard for EBEX.

We also examined the spatial variability of net radiation. For this purpose, data from the net radiometers deployed at each site are shown in Figure 6. The total variability is only on the order of 20 W m⁻² though the point-to-point differences were larger by about a factor of 3. Some of this variability might have been due to slight misleveling of the sensors. In general, the spatial variability of the fluxes was not large, despite the differences apparent in Figure 1.

Considerable effort was expended to determine G, including heating of the canopy and the soil above the heat flux plates. This effort included destructive measurements of wet and dry biomass and leaf and stem temperatures, all sorted by height within the canopy. Figure 7 shows that the soil heat flux measured at 5 cm



Figure 6: The diurnal composite over all days of the net radiation measured by the Q^{*7} radiometers at all sites minus that at site 5.



Figure 7: The diurnal composite over all sites and days of the total surface heating G and the various terms comprising it. G_{soil} is the heat flux measured by the heat flux plates at 5 cm depth, S_{soil} is the heat storage in the soil above the heat flux plate, S_{canopy} is the heat storage by the above-ground plant biomass, and S_{air} is the heat storage by air in the canopy.

depth and the heat storage above it were about equal in magnitude and together made up most of the total for G. Obtaining good measurements of the soil moisture is critical for determining the heat storage in the soil. Heat storage in the canopy averaged less than 10 W m⁻² and the heating of the air within the canopy was so small that it is not visible in this figure.

Finally, we can produce a total energy budget for EBEX. Figure 8 shows that the balance is good at night, with $G \approx R_{net}$. At midday, R_{net} is 680 W m⁻², LE is 460 W m⁻², H is 60 W m⁻² and G is 50 W m⁻².



Figure 8: The diurnal composite of the surface energy balance for EBEX. Here R_{net} is from the Q*7 net radiometers.

Thus, the imbalance is 110 W m⁻² or 16% of R_{net} . Clearly, more work remains to be done.

4 SUMMARY

EBEX collected an excellent data set for evaluating the surface energy balance. We have found that critical attention to calibration, maintenance, and software corrections of data from all sensors is essential to obtain fluxes good to 10 W m⁻². Despite this effort, the EBEX data set still contains a large imbalance. Work will continue to identify the source of this imbalance.

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REFERENCES

Foken, T. and S. Oncley, 1995, "A report on the workshop: Instrumental and methodical problems of land-surface flux measurements", *Bull. Amer. Met. Soc.*, 76, 1191-1193.