U.S. DEPARTMENT OF ENERGY

Energy Balance Bowen Ratio (EBBR) Handbook

DR Cook

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ARM

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DR Cook, Argonne National Laboratory

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1.0   General Overview

The Energy Balance Bowen Ratio (EBBR) system produces 30-minute estimates of the vertical fluxes of sensible and latent heat at the local surface. Flux estimates are calculated from observations of net radiation, soil surface heat flux, and the vertical gradients of temperature and relative humidity (RH). Meteorological data collected by the EBBR are used to calculate bulk aerodynamic fluxes, which are used in the Bulk Aerodynamic Technique (BA) EBBR value-added product (VAP) to replace sunrise and sunset spikes in the flux data. A unique aspect of the system is the automatic exchange mechanism (AEM), which helps to reduce errors from instrument offset drift.

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3.0   Deployment Locations and History

Table 1. EBBR status.

Extended Facility	Facility Location	Date Installed	Date Removed	Status
2	Hillsboro, KS	05/23/1997	10/20/2009	Removed
4	Plevna, KS	04/03/1993	09/26/2011	Removed
7	Elk Falls, KS	08/29/1993	11/14/2011	Removed

Extended Facility	Facility Location	Date Installed	Date Removed	Status
8	Coldwater, KS	12/08/1992	11/10/2009	Removed
9	Ashton, KS	12/10/1992		Operational
12	Pawhuska, OK	08/29/1993		Operational
13	Lamont, OK (at the Central Facility	09/14/1992		Operational
15	Ringwood, OK	09/16/1992		Operational
18	Morris, OK	09/10/1997	11/17/2009	Removed
19	El Reno, OK	05/29/1997	09/19/2011	Removed
20	Meeker, OK	04/05/1993	11/17/2011	Removed
22	Cordell, OK	04/05/1993	12/1/2009	Removed
25	Seminole, OK	10/22/1997	04/08/2002	Removed
26	Cement, OK	06/10/1992	12/17/2009	Removed
27	Earlsboro, OK	05/02/2003	12/4/2009	Removed
32	Medford, OK	09/28/2011		Operational
34	Maple City, KS	09/02/2011		Operational
35	Tryon, OK	10/05/2011		Operational
36	Marshall, OK	09/28/2011		Operational
39	Morrison, OK	09/2015		Expected Install
40	Pawnee, OK	09/2015		Expected Install

4.0 Near-Real-Time Data Plots

To view near-real-time plots of EBBR data, visit DQ Explorer at http://dq.arm.gov/dq-explorer/cgi-bin/main/metrics or NCVweb at https://plot.dmf.arm.gov/ncvweb/ncvweb.cgi. For the NCV web page, choose "sgp" from the menu, and click the "Submit Site" button. Then choose sgp30ebbrE##.b1 from the next menu (## stands for extended facility number) and click the "Submit DataStream" button. Now highlight a date or range of dates for which you are interested in seeing EBBR data and click on the "Plot File" button. Choose a variable for the Y axis and click on the "Apply Changes" button to plot the data. Time series and multiple plots can also be created.

5.0 Data Description and Examples

5.1 Data File Contents

5.1.1 Primary Variables and Expected Uncertainty

30 minutes:
Sensible Heat Flux (h): 10% uncertainty

Latent Heat Flux (e): 10% uncertainty
Net Radiation (q): 5% uncertainty
Average Soil Surface Heat Flux (ave_shf): 10% uncertainty

5.1.1.1   Definition of Uncertainty

We define uncertainty as the range of probable maximum deviation of a measured value from the true value within a 95% confidence interval. Given a bias (mean) error B and uncorrelated random errors characterized by a variance σ^2, the root-mean-square error (RMSE) is defined as the vector sum of these:

$$RMSE = \left(B^2 + \sigma^2\right)^{1/2}.$$

(B may be generalized to be the sum of the various contributors to the bias and σ^2 the sum of the variances of the contributors to the random errors). To determine the 95% confidence interval, we use the Student's t distribution: $t_{n;0.025} \approx 2$, assuming the RMSE was computed for a reasonably large ensemble. Then the *uncertainty* is calculated as twice the RMSE.

5.1.2   Secondary/Underlying Variables

30 minutes:
tair_top
tair_bot
thum_top
thum_bot
hum_top
hum_bot
vp_top
vp_bot
pres
sm1, sm2, sm3, sm4, sm5
ts1, ts2, ts3, ts4, ts5
shf1, shf2, shf3, shf4, shf5
c_shf1, c_shf2, c_shf3, c_shf4, c_shf5
cs1, cs2, cs3, cs4, cs5
ces1, ces2, ces3, ces4, ces5
g1, g2, g3, g4, g5
bowen
wind_s
res_ws
wind_d

15 minutes:
rr_tref
rr_thum_r
rr_thum_l
rr_ts1, rr_ts2, rr_ts3, rr_ts4, rr_ts5
r_sm1, r_sm2, r_sm3, r_sm4, r_sm5
mv_hum_r
mv_hum_l

mv_pres
mv_q
mv_wind_d
mv_home
mv_hft1, mv_hft2, mv_hft3, mv_hft4, mv_hft5
tair_r
tair_l
wind_s

5 minutes:
tref
tair_top
tair_bot
thum_top
thum_bot
hum_top
hum_bot
vp_top
vp_bot
q
pres
wind_s
res_ws
wind_d

5.1.3   Diagnostic Variables

30 minutes:
tref
sigma_wd
hom_15
hom_30

15 minute:
bat
signature

5 minute:
sigma_wd
home

5.1.4   Data Quality Flags

30 minutes:
qcmin1-24
qcmax1-24
qcdelta1-24
qcmin25-48
qcmax25-48
qcdelta25-48

qcmin49-72
qcmax49-72
qcdelta49-72

15 minutes:
qcmin1-24
qcmax1-24
qcdelta1-24
qcmin25-48
qcmax25-48
qcdelta25-48

5.1.5   Dimension Variables

Note: lat, lon, and alt refer to the ground surface, not to the instrument system height

30, 15, and 5 minute:
lat
lon
alt
base_time
time_offset

5.2 Annotated Examples

The following plot of sensible (h) and latent (e) heat fluxes show a normal diurnal variation in heat fluxes, with latent heat flux being mostly negative during nighttime hours, as evaporation continues, and sensible heat flux being positive. During daylight hours, both h and e are negative, as energy is lost from the surface. The plot also shows the spikes in the data that can occur at sunrise and sunset when the Bowen ratio is near -1 (see the Bowen ratios annotated on the plot, near the data spikes).

Ringwood 05/18/2000

Figure 1. Plot showing sensible (h) and latent (e) heat fluxes showing a normal diurnal variation in heat fluxes. Spikes in the data occur at sunrise and sunset when the Bowen ratio is near -1.

The BA EBBR VAP replaces the spiked data with fluxes calculated with the BA. The resultant combined flux data are shown in the next plot.
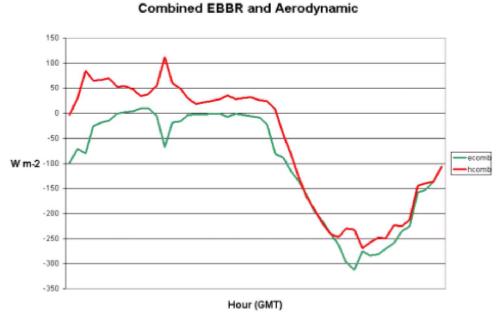
Combined EBBR and Aerodynamic

Figure 2. Plot showing the spiked data replaced by the BA EBBR VAP with fluxes calculated with the BA.

5.3 User Notes and Known Problems

Some conditions do not require Data Quality Reports (DQRs) because they occur somewhat frequently. These conditions include spikes in the sensible and latent heat fluxes when the Bowen ratio is near -1, short periods when the AEM is not functioning properly (this can be detected from the quality control [QC] checks in the data files), and short periods of missing data.

Common instrumentation problems include the following:

- condensation or frost on the net radiometer upper polyethylene dome (this can persist well into daylight hours)

- net radiometer desiccant degradation

- holes in the net radiometer top dome caused by bird claws (this can result in water in the net radiometer if the dome is not replaced before precipitation occurs)

- soil sensors pulled from the ground or chewed by animals

- a blown fuse in the AEM when the belt slides bind against the track

- seized bearings in wind instruments

- aging of sensors and electronic components

- loosened electronic connections.

Preventative maintenance visits every two weeks and instrument mentor quality assurance activities are designed to detect and correct these problems to reduce the amount of incorrect data collected.

5.4 Frequently Asked Questions

How is the latent heat flux and sensible heat flux derived?

The Bowen ratio technique is used to determine Bowen ratio, assuming that the transfer coefficients of heat and water vapor are the same. The Bowen ratio is then used in conjunction with net radiation and soil surface heat flux measurements to determine sensible and latent heat flux based on a budget approach. More details are provided in Section 7.2, Theory of Operation.

What is the sign convention used for the energy flux densities?

All energy flux densities have a positive sign when directed toward the surface, and negative when directed away. For example, values of sensible (h) and latent heat flux (e) could be 0 to -600 watts per meter squared during the daytime in the summer.

In the design of the EBBR stations, which data are considered the most useful to Atmospheric Radiation Measurement (ARM) Science Team members?

The EBBR stations were designed primarily for computation of the sensible and latent heat fluxes. The soil temperature, moisture, and heat fluxes are measured in the upper 5 cm of the soil and therefore are not very useful for determining root zone soil moisture and soil heat flow. Other observations, such as air

temperature, RH, atmospheric pressure, and wind speed and direction are secondary measurements; Surface Meteorological Instrumentation (MET) measurements, where available, should be used as the absolute measurements of these quantities. For example, the EBBR atmospheric pressure data are not measured with sufficient accuracy for many applications, whereas the MET pressure data have a smaller uncertainty and might be suitable for calculations of geostrophic winds. Other sources of reliable surface meteorological data are available as external data for the ARM Program from the Oklahoma Mesonet and from the Kansas network. The data user is encouraged to use the data from the MET for such observations.

EBBR data are collected only at the Southern Great Plains (SGP) extended facilities, including one at the Central Facility and some that are collocated with boundary facilities, and where the local surface is not tilled. Eddy correlation stations exist at nearly half of the extended facilities to sample the latent heat, sensible heat, and momentum fluxes above tilled cropland.

EBBR data can be used to compute momentum fluxes with a bulk aerodynamic approach. This approach is used as the basis for the calculation of sensible and latent heat fluxes by the BA EBBR VAP (Wesely etal. 1995).

What do AEM home signals indicate?

The AEM home signal outputs in the 5-, 15-, and 30-minute datastreams are in units of millivolts DC. The circuitry producing the millivolt output is fairly rudimentary, and therefore the millivolt value is

proportional to the DC voltage output of the EBBR power supply (solar/AC charged battery). The home signal can therefore vary significantly diurnally and can fall to unacceptable levels for the 15-minute value if battery performance degrades too much.

During the first and third quarter hours, the right side (looking from behind the AEM) aspirated radiation shield (housing temperature and RH probes) is normally in the "bottom" (lowest elevation) position, and the left side is in the "top" (greatest elevation) position. During this AEM state, the 5-minute "home," 15-minute "mv_home", and 30-minute "home_15" values should be between 40 and 55.

During the second and fourth quarter hours, the left side (looking from behind the AEM) aspirated radiation shield (housing temperature and RH probes) is normally in the "bottom" (lowest elevation) position, and the right side is in the "top" (greatest elevation) position. During this AEM state, the 5-minute "home," 15-minute "mv_home," and 30-minute "home_30" values should be between 15 and 30.

What soil measurements are made by the EBBR stations?

Five soil heat flow sensors are located at a depth of 5 cm from the surface, five long platinum resistance temperature detectors (PRTDs) integrate the temperature from the surface to a depth of 5 cm, and five soil moisture probes are located at a depth of 2.5 cm. Each set of five soil sensors is averaged. Because soil is not horizontally homogeneous, the sensors are spaced out in the soil locally to provide representative samples.

The purpose of these sensors is to compute one term, the surface soil heat flux. The soil temperature and moisture probes allow calculation of energy storage in the layer of soil between the surface and the heat flow plate depth of 5 cm. The soil moisture probes allow the soil heat flow measurements to be adjusted for the conductivity of the soil.

The sensible and latent heat fluxes are computed by the EBBR data logger with the standard energy balance equation, in which the surface soil heat flux is usually a relatively small term. The surface soil heat flux term cannot be precisely recalculated from the raw information because of the way the soil energy storage term is computed with the EBBR data logger, but, in principle, the raw information can be used to recompute the sensible and latent heat fluxes with only a few percent error.

If some of the soil probes are not working, can sensible and latent heat fluxes be recalculated?

Yes. The remaining working soil probe sets can be used to calculate an average surface soil heat flux. See the procedure in Section 7.2, Theory of Operation.

What type of diurnal trends should appear in the EBBR data?

Some examples of diurnal trends can be seen in various textbooks and articles. For example, some data are shown in the special FIFE issue of the *Journal of Geophysical Research* (97(D17):18343-19110), e.g.,Fritschen et al. (1992). The ARM Facility uses a Fritschen-type EBBR station.

What can be said about the quality of the EBBR data?

The EBBR systems sometimes experience hardware problems. For example, the AEM will sometimes malfunction. Some problems, like this one, can be discerned by looking at the data quality flags.

The following information should be useful for interpretation of the quality of data from the EBBR stations. Data quality flags should be used to detect when the AEM is functioning properly. The rate of AEM failure has been high at times. When it is not working, the estimates of sensible and latent heat flux are unreliable and should not be used for any scientific investigations, even if the flux estimates appear to be reasonable.

To use the metadata on the AEM, the user should become familiar with the field and global attributes described in a dump of the netCDF header. The fields are defined there, and, in data sets recently provided, the configuration of the data quality flags is briefly described at the end of the list of the global attributes. The flags themselves are contained in numbers at the end of the data listing. The next paragraph provides some suggestions on the QC numbers (qcmin# and qcmax#) and the embedded flags relevant to the AEM.

QC flags in the standard 30-minute data interval indicate when the AEM is working for each half hour in the time series. The particular QC flags of interest are the sixth and seventh bits of the 24-bit binary numbers representing qcmin49-72 and qcmax49-72. The sixth bit of qcmin49-72 is set to zero when the home_15 is greater than 35 mV, and to unity when less. The sixth bit of qcmax49-72 is set to zero when the home_15 is less than 70, and to unity when greater. A similar set of criteria are applied to the seventh bit, but with a minimum of 15 and maximum of 34.999999. Alternatively, if you choose not to convert the QC numbers to binary form, you can inspect the values of home_15 and home_30 to determine if they fall in the desired range. Because the limit checks on the home signals were not properly set prior to April7,1993, you must inspect home_15 and home_30, rather than qcmin# and qcmax# for data collected prior to that date.

The QC flags should routinely be used for all of the variables. For some variables, however, QC flags have not been set, and for some variables (e.g., average soil heat flux [ave_shf], latent heat flux [e], and sensible heat flux [h]), flags were not set until late May 1998, as is evident in the listing of the field attributes. Nevertheless, some information can be obtained by inspection of the data if you are familiar with typical values. For example, Bowen ratios tend to be positive during the day and negative at night. Daytime values are usually between 0 and 2, and nighttime values can vary widely between positive values and -50. A negative Bowen ratio during daylight hours should be considered as possibly indicating suspect sensible and/or latent heat flux values. During transition times lasting up to two half hours near sunrise and sunset, the magnitude of the Bowen ratio can sometimes be quite large, in which case the sensible and latent heat flux values should be viewed as suspect. Although no QC flags were set for latent and sensible heat flux, values smaller than -1000 watts per meter squared and larger than 200watts per meter squared are clearly suspect.

Routine checks reveal an expected offset drift of the RH probe of about +2% per year caused by aging and dirt contamination of the RH sensing element. This drift has also been observed in the Tower and MET RH probes. Although this affects the absolute accuracy of the RH measurement, it does not adversely affect the 30-minute vapor pressure difference calculated from the RH and temperature measurements because the RH probes drift at approximately the same rate, and the AEM exchanging

Bowen ratio technique reduces offset effects. Recalibration after two years of use is usually recommended to keep the RH probes within their "as new" absolute accuracy specification; this is the goal of the EBBR recalibration program conducted every two years.

The absolute value of the home signals varies with the voltage of the battery that powers the EBBR data acquisition system. When the battery condition is good, the home_15 value is typically between 40 and 55; the home_30 value is typically between 15 and 30. When battery condition is low, the home signals can be slightly lower, but then the data from some individual sensors are questionable. Instances have occurred where low battery condition allowed some sensors to function while others did not. DQRs are written to identify such problems.

Unfortunately, the AEM does not always switch and occasionally hangs up. Four cases are common:

1. AEM fuse blown. When the fuse blows, the housing positions on the AEM are uncertain and usually yield home_15 and/or home_30 values of zero, although E15 at Ringwood, Oklahoma, showed -2.0 in this condition in May 1994. Usually the fuse blows because of too much friction on the exchange mechanism resulting from freezing rain or snow, built-up dirt, or an electrical or electronic failure.

2. AEM stuck at one position. Usually the right housing will stick in the down position (sometimes referred to in site operations log messages as the home position). When this happens, the home_15 and home_30 signal outputs are usually both equal to the proper home_30 value, if the AEM fuse has not blown. There are exceptions to this, of course, which included a period at the Central Facility EBBR in late 1992 when both home signals were 35.

3. AEM stuck between the 15- and 30-minute positions. This situation usually produces a very small negative home value for both home_15 and home_30, such as -0.2.

4. AEM removed for service. Occasionally, an AEM has been removed from service for repair when no replacements were available (e.g., when the EBBR at E9, Ashton, Kansas, was removed on April5,1994). A resistor in the AEM circuitry had burned out, leaving the left housing in the bottom position (a rarity). This had resulted in both home signals showing somewhere from 67 to 73. After the AEM was removed, the aspirated housings were tied to the EBBR frame, approximately a meter apart. Without the AEM circuitry being present, the home signals floated to the thousands. On April19, a refurbished AEM was installed and the home signals returned to normal.

The list above illustrates only some of the possibilities. Generally, whatever their absolute values, if the home_15 and home_30 values are practically the same in the 30-minute data, at least one of them is incorrect, indicating that the sensible and latent heat flux estimates are suspect. Unless both the home_15 and home_30 values are within proper ranges, the sensible and latent heat values must be considered incorrect. No other interpretation is appropriate. Even if we know the AEM position situation and could thus recalculate fluxes from the available data, those fluxes would still be corrupted with calibration offsets, which are normally removed via the AEM switching process.

Most users of the EBBR data only receive the 30-minute data and not the 5- or 15-minute data. The QC flags in the 15-minute data might be useful for a comprehensive evaluation of each EBBR sensor. For example, the qcmin# check for battery condition in the 15-minute data is set to the lowest value at which the sensors will typically operate reliably. Also, soil moisture resistance ratios (rr_sm#, used before April1996) or soil moisture resistance (r_sm#, used beginning in April 1996) could be examined to help determine when individual soil moisture values are reliable. However, we do not expect every user of the

EBBR to obtain the 15-minute data for such analyses. Finally, users of the data are cautioned that the reliability and accuracy of some individual sensors, such as soil moisture sensors, may be not optimal. The EBBR system was not designed to observe all quantities extremely well because its primary purpose is to provide sensible and latent heat flux estimates, which are not particularly sensitive to the uncertainties of some of the variables. For example, if accurate, reliable estimates of barometric pressure and air temperature are needed, the values supplied by MET or from external data sets, such as those from the Oklahoma Mesonet, should be used. For soil moisture and temperature, we consider the EBBR observations to be mostly inadequate for use in land-surface process and hydrological models or submodels. On the other hand, we expect high-quality data on net radiation from EBBR stations because it is crucial in the energy balance calculations. We expect soil heat flux values to be good because they enter directly into the surface energy balance calculations (but are typically small in magnitude compared to net radiation). Unforeseen types of failures sometimes occur, e.g., the ventilator for one of the temperature and humidity sensors stops. Such problems are usually described in DQRs that are available for data users.

When the Bowen ratio is between -1.6 and -0.45, "spikes" can occur in the latent and sensible heat flux values.

What are likely difficulties in comparing surface heat fluxes measured by EBBR stations to results of numerical modeling efforts?

One of the greatest difficulties in comparing model versus field data on surface heat fluxes is caused by model calculations requiring soil moisture information. The soil moisture across the SGP site can be quite variable for summertime conditions. EBBR soil moisture data provide measurements of average moisture content only in the top 5 cm. During 1996 and 1997, an effort led by Jeanne Schneider, University of Oklahoma, and supported by the National Oceanic and Atmospheric Administration for GEWEX Continental-Scale International Project (GCIP), installed soil water and temperature system (SWATS) profiling instrumentation at every SGP extended facility, including every location with an EBBR station. SWATS soil moisture and soil temperature data should be used for modeling efforts, instead of the EBBR soil moisture and temperature data.

Since summer 1995, at least three science team groups have tried comparing model outputs with SGP site data: Jim Liljegren working with Chris Doran at Pacific Northwest Laboratory; Marina Zivkovic working with Jean-Francois Louis at Atmos. & Environmental Research, Inc., in Cambridge, Massachusetts; and Sarah Fox working with Lee Harrison and others at the State University of New ork at Albany.

A cooperative program of sorts that has looked extensively at this type of modeling is PILPS (Project for Intercomparison of Land-surface Schemes). One conclusion of PILPS is that more observational data are needed for developing large-scale models. For example, an article by Betts et al. (1993) carries out a critical evaluation of European Center for Medium Range Weather Forecasts (ECMWF) model outputs by using FIFE data.

Some other potentially informative articles are as follows:

Avissar, R, and MM Verstraete. 1990. "The representation of continental surface processes in atmospheric models." *Reviews of Geophysics* 28: 35-42, doi:10.1029/RG028i001p00035..

Dickinson, RE, RM Errico, F Giorgi, and GT Bates. 1989. "A regional climate model for the Western United States." *Climatic Change* 15: 383-422, doi:10.1007/BF00240465.

Shuttleworth, WJ. 1991. "1. Insight from large-scale observational studies of land/atmosphere interactions." *Surveys in Geophysics* 12: 3-30, doi:10.1007/978-94-009-2155-9.1.

6.0   Data Quality

6.1   Data Quality Health and Status

The status of the measurements made by the EBBR system can be found by going to the ARM DQ Explorer web page at http://dq.arm.gov/dq-explorer/cgi-bin/main/metrics.

6.2   Data Reviews by Instrument Mentor

Monthly reviews of the EBBR data were prepared by the mentor and submitted to the Instrument Mentor Monthly Summary (IMMS) report database until these ended in late 2014. These reports are available on the EBBR web page.

Beginning in FY2006, Data Quality Reports are not written for missing data or for situations when QC flags clearly show that the data are incorrect (this is true for most of the conditions listed below). DQRs are written for periods when data are incorrect, when the situation is not represented by QC flags in the data, and it is s not obvious that the data should have been flagged as incorrect.

6.3   Data Assessments by Site Scientist/Data Quality Office

The following guidance has been provided by the EBBR mentor for use by the Data Quality Office (DQO) in preparing their weekly assessment report for the EBBR systems.

<div align="center">

EBBR Data Quality Guidance

David R. Cook
16 December 2006

</div>

Introduction: The best way to tell someone what to look for in assessing the EBBR data is to describe conditions that reflect correct and incorrect data. For the most part, the QC checks provide adequate guidance. However, there are conditions for which the QC flags do not provide the needed guidance to be able to interpret the correctness of the data. Therefore, please use the information below as further guidance.

Primary Measurements: e (latent heat flux), h (sensible heat flux), q (net radiation), ave_shf (average surface soil heat flux); le and h are calculated, whereas q and ave_shf are measured. The QC limits set in the ingest are appropriate for the measurements (primary and otherwise), although there are times when legitimate values fall outside the QC limits.

Nuisance QC Flags: The Bowen QC flag is frequently tripped, particularly at sunrise or sunset, when the gradient of temperature can be near zero. This condition produces spikes in h and e, which would be quite

obvious without the Bowen QC flag. Tripping of the Bowen QC flag near sunrise or sunset should not be reported in the DQO assessment reports. The hum_top and hum_bot QC flags will trip when the RH reported by the T/RH sensor exceeds a certain value. However, the absolute accuracy of the RH measurements is not important; the difference between them is used to determine e. Therefore, the hum_top and hum_bot QC flag condition should not be reported in the DQO assessment reports.

Comparison of Data at Different EBBR Sites: Generally, the measurements can be compared favorably with those at adjacent sites, keeping in mind that climate conditions from one side of the SGP facility to another can differ sharply. There are some soil and surface vegetation differences between sites as well, so comparisons may show significant differences.

Comparison of Data with the ECOR: The only collocated ECOR and EBBR are at the SGP Central Facility (CF) and at EF39, Morrison, OK. Caution must be used in the comparison of the two systems at SGP CF because they may see different vegetation surfaces (Cook et al. 2006). At the CF the best comparison can be made for straight north or northwest wind directions, when both systems view the same grass surface. For other directions, the two systems are viewing different vegetation surfaces and the fluxes from the two will probably not be similar, unless perhaps, the ground is snow covered. At EF39 the EBBR and ECOR see the same surface, whether the wind blows over the wheat or the grass. Sensible and latent heat flux, and wind speed and direction measurements, could be compared for adjacent ECOR and EBBR sites, again remembering that there are likely to be climatologically driven differences.

Comparison of Data with the MET: MET systems are collocated with EBBR systems at 8 of the 14EBBR sites (exceptions are E2, E12, E18, E19, E22, and E26). The measurements of upper EBBR temperature, RH, and vapor pressure can be directly compared with the MET temperature, RH, and vapor pressure. Even so, the EBBR RH may often be greater than that from the MET, as it is allowed to drift upwards with time for longer than is allowed for the MET. Wind speed and direction for the two systems are at different heights (MET 10 m, EBBR ~3 m), so it is normally expected that the MET wind speed will be greater than the EBBR wind speed. Wind direction may be very similar, but may be somewhat different if a frontal passage or strong advection is taking place. The EBBR pressure measurement is not as accurate as that made by the MET, but their trends and general level may be compared in a gross way.

Comparison of EBBR Net Radiation with Solar and Infrared Station (SIRS) Net Radiation: EBBR net radiation measurements do not agree with SIRS net radiation calculations when the effective sky temperature is less than about -20 °C and the EBBR net radiometer sensitivity decreases rapidly with the further decrease in effective sky temperature. First, the REBS longwave calibration is not performed to very low temperatures, and second, the design of the net radiometer may not allow for accurate, low, effective, sky temperature measurements. Infrared thermometer (IRT), atmospheric emitted radiance interferometer (AERI), and SIRS net radiation measurements are more accurate under the condition of low effective sky temperatures.

The result of this situation is that the EBBR overestimates or underestimates (it sounds odd, but it can be either) the nighttime sensible heat flux (direction is to the surface) and overestimates (sometimes by possibly a factor of 3) the nighttime latent heat flux. This is not a major concern since the nighttime fluxes are usually quite small anyway. Daytime fluxes are also affected, but since shortwave radiation dominates the radiant energy budget, the sensible and latent heat fluxes are both overestimated by only about 5 percent during a sunny day and by about 2 percent on a cloudy day during summertime. These errors are well within the 10 percent system error of the EBBR.

Common Conditions Reflecting Correct or Incorrect Data:

The EBBR data are only useful for particular wind directions at each extended facility. Please use the following resources to help in interpreting the EBBR data:

1. QC flags in the EBBR data.

2. IMMS at http://www.db.arm.gov/IMMS/.

3. The information below on wind direction dependencies and conditions that commonly cause incorrect data.

Wind Direction Dependencies (numbers are wind direction in degrees); note that there are wind directions at most sites for which the fetch is insufficient and therefore EBBR data are invalid. Appropriate fetch was determined from a 1/40 measurement height-to-fetch ratio, resulting in a required minimum fetch of 120m. Particular attention should be paid to the limited valid wind directions for the Central Facility EBBR. The surface vegetation type for the EBBRs is grazed or ungrazed grassland (refer to the EFSCO for state):

- EF2: 71–137, 223–289
- EF4: 0–158, 202–360
- EF7: 0–244, 296–360
- EF8: 0–224, 314–360
- EF9: 0–360
- EF12: 0–360
- EF13: 0–52, 142–194, 328–360
- EF15: 133–360
- EF18: 138–325
- EF19: 0–133, 151–360
- EF20: 0–230, 310–360
- EF22: 0–49, 139–360
- EF25: 30–300
- EF26: 0–33, 243–360
- EF27: 20–156
- EF32: 0-360
- EF34: 0-360
- EF35: 0-360
- EF36: 0-360
- EF39: 100-260 wheat, 280-360 and 0-80 un-grazed grass

- EF40: 0-360

Some conditions that commonly cause the EBBR primary measurements to be incorrect or missing data are as follows:

- Sensible and latent heat fluxes are not accurate during times when the Automatic Exchange Mechanism (AEM) is not functioning properly. The AEM switches the gradient measuring instrumentation between the top and bottom positions every 15 minutes; this reduces the effects of instrument offsets. Sometimes the AEM does not reach its full extent of travel, resulting in the home signal being zero.

- Sensible and latent heat fluxes are sometimes incorrect when surface soil heat flow is out of range, as seen in the average soil heat flux (ave_shf).

- Very light winds may be seen at nights for brief periods. Wind direction flops around a lot during low wind conditions (< 1.5 m/s) and is often unreliable during those periods.

- Missing data periods occur at times. This is usually a site data system collection/communication problem; it can also occur during replacement of the system with a newly calibrated unit. Missing data are sometimes filled in later from manual or automatic re-collection of the data.

6.4 VAPs and Quality Measurement Experiments (QMEs)

The BA EBBR VAP represents a recalculation of sensible and latent heat fluxes using wind speed and temperature gradient information in conjunction with a bulk aerodynamic estimation technique. This VAP has been implemented, and 30-minute average files are available in the ARM Data Archive from 1995. Vegetation height and wind speed are used to determine aerodynamic quantities that allow the calculation of sensible and latent heat flux independent from measurements of net radiation and soil surface heat flux. These calculations help to produce more reasonable flux estimates when the Bowen ratio is between -1.6 and -0.45 (the Bowen ratio technique often produces unreasonable flux values under this condition). Data source names take the form "sgp30baebbrE13.c1." Presently, the files can be found in the ARM Data Archive by looking under c1 data sources. Results from the BA EBBR VAP can be seen in the second plot in Section5.2, Annotated Examples.

A second VAP involves the recalculation of sensible and latent heat fluxes using Solar and Infrared Station (SIRS) net radiation information; however, this VAP has not been implemented. This approach may help to improve flux estimates during times when the EBBR net radiation data are corrupted by dew, frost, or condensation inside or outside of the net radiometer domes.

EBBR-related QMEs could include:

- Comparison of EBBR-measured net radiation and SIRS-calculated net radiation. Comparison plots of EBBR net radiation and SIRS-calculated net radiation are produced by the DQO and displayed on the DQ Explorer website. These comparison plots reveal significant differences between these two systems at times. A QME has not been performed as of yet.

- Comparison of sensible and latent heat fluxes from EBBR and eddy correlation (ECOR) systems can only be made at the SGP Central Facility (only for very limited wind directions; within 30 degrees east or west of north) and at EF39.

7.0   Instrument Details

7.1   Detailed Description

7.1.1   List of Components

- Vaisala T/RH probes at two heights (1-m separation), in aspirators

- PRTD temperature probes at two heights (1-m separation), in aspirators

- REBS Q*7.1 Net Radiometer (at 2 m typical)

- REBS SMP-2 (5 sets) Soil Moisture Probes at 2.5 cm depth

- REBS HFT-3 (5 sets) Soil Heat Flow Plates at 5 cm depth

- REBS STP-1 (5 sets) Soil Temperature Probes, integrated 0 to 5 cm

- Met One Instruments 090C or 090D Barometric Pressure sensor (in enclosure)

- Met One 020C Wind Direction sensor at 2.5 m

- Met One 010C Wind Speed sensor at 2.5 m

- PRTD Reference temperature of control box

- REBS AEM

- Pipe network structure for mounting of the instrumentation

- Solar panel, battery, AC charger power source

- Enclosure holding Campbell CR10, multiplexers, J-panels, communication equipment.

7.1.2   System Configuration and Measurement Methods

The EBBR sensors (except for soil probes) are mounted on a triangular pipe framework that sits on the soil surface. The net radiometer mount extends from the south end of the EBBR frame.

A unique aspect of the system is the AEM, which helps to reduce errors from instrument-offset drift. The AEM extends from the north end of the frame. Aspirated radiation shields (which house the air temperature and temperature/RH probes) are attached to the AEM. The openings of the aspirated radiation shields face north to reduce radiation error from direct sunlight.

The soil probes are buried just outside the view of and in an arc to the south of the net radiometer.

The heights of the AEM aspirators are different at different extended facilities and depend on maximum vegetation height; the vertical separation between the two aspirators is 1 m at all extended facilities. The heights or depths of all other sensors are the same at all facilities.

The reference temperature sensor, barometric pressure sensor, data logger equipment, and communication equipment are located in a control box (weatherproof enclosure), which is attached at the northeast corner of the EBBR frame.

The local area of influence upon Bowen ratio measurements is contained within a horizontal distance of approximately 20 times the height of the top aspirated radiation shield on the AEM. This distance varies among the different extended facilities and for different times of the year because of differences in maximum vegetation height, and therefore the height at which the AEM is installed.

The manufacturer's (REBS) name for these systems is SEBS (Surface Energy Balance System); this name appears in their systems documentation.

7.1.3   Specifications

The accuracies cited below are generally those stated by the manufacturer. They are sensor-absolute accuracies and do not include the effects of system (i.e., data logger) accuracies. Although it is not known how some of the manufacturers have determined sensor accuracy, it is properly the root square sum of any nonlinearity, hysteresis, and non-repeatability, usually referenced as percentage of full scale.

The detection limit is normally restricted to the range (sometimes called Calibrated Operating Range) over which the accuracy applies. In the case of the EBBR, some of the detection limits are those determined by the vendor (REBS) who performed the calibration, not by the manufacturer of the sensor. Some manufacturers also specify an Operating Temperature Range in which the sensor will function both physically and electronically, even though the calibration may not be appropriate for use throughout that range. When the manufacturer or the calibrating vendor has listed no detection limits, none are stated below.

Air temperatures: Chromel-constantan thermocouple, Omega Engineering Inc., REBS Model # ATP-1, Detection Limits -30 to 40°C, Accuracy +/- 0.5°C.

Temperature/RH Probe: Operating Temperature Range -20 to 60°C. Temperature: Platinum Resistance Temperature Detector (PRTD); Detection Limits -30 to 40°C, Accuracy +/- 0.2°C RH: Capacitive element, Vaisala Inc., Model #s HMP 35A and HMP 35D; Detection Limits 0% to 100% RH, Accuracy +/- 2% (0-90% RH), +/- 3% (90-100%), uncertainty of RH calibration +/- 1.2%.

Soil Temperature: Platinum Resistance Temperature Detector, MINCO Products, Inc., REBS Model # STP-1, MINCO Model # XS11PA40T260X36(D), Detection Limits -30 to 40°C, Accuracy +/- 0.5°C.

Soil Moisture: Soil Moisture Probe (fiberglass and stainless steel screen mesh sandwich), Soiltest, Inc., REBS Model # SMP-2, Soiltest Model # MC-300, Accuracy not specified by manufacturer (varies significantly depending on soil moisture and soil type). Detection limits for this sensor are limited by the ability to fit a polynomial to the calibration data; for the SGP site, the detection limits are approximately 1% to 50% by volume.

Soil Heat Flow: Soil Heat Flow Probes, Radiation & Energy Balance Systems, Inc., Model #s HFT-3, HFT3.1, Accuracy not specified by manufacturer.

Barometric Pressure: Barometric Pressure Sensor, Met One Instruments, Model #s 090C-24/30-1, Detection Limits 24 to 30 kPa; 090C-26/32-1, Detection Limits 26 to 32 kPa; 090D-26/32-1, Detection Limits 26 to 32 kPa; Accuracy for all +/- 0.14 kPa.

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Net Radiation: Net Radiometer, Radiation & Energy Balance Systems, Inc., Model Q*6.1 or Q*7.1, Accuracy +/- 5% of full-scale reading.

Wind Direction: Wind Direction Sensor, Met One Instruments, Model #s 5470, 020C, Detection Limits 0 to 360° physical (for greater than 0.3 ms-1 wind speed), 0 to 356° electrical, Accuracy +/- 3°.

Wind Speed: Wind Speed Sensor, Met One Instruments, model #s 010B and 010C, Operating Temperature Range -50 to 85°C, Detection Limits 0.27 to 50 ms-1, Accuracy +/- 1% of reading. Operational Limit on speed 60 ms-1.

Data logger: Campbell Scientific, Inc., Model CR10, Detection Limits vary by voltage range selected, Accuracy +/- 0.1% of full scale reading.

7.2   Theory of Operation

The EBBR stations use a standard Bowen ratio approach that has been described by textbooks and articles. A general description can be found in Brutsaert (1982). For an article, see the special FIFE issue of the *Journal of Geophysical Research* (97: 18549).

The surface energy balance equation is used:

q + ave-shf + h + e = 0,

where q is net radiation, ave_shf is the ground surface heat flow, h is sensible heat flux, and e is latent heat flux. The units for the terms in the equation above are watts per meter squared.

ave_shf is measured with five sets of soil heat flow, soil temperature, and soil moisture probes. Soil heat flow at 5 cm (shf1, shf2, shf3, shf4, shf5), measured with soil heat flow plates, and soil energy storage (ces1, ces2, ces3, ces4, ces5) in the 0–5 cm layer (measured as the change in temperature with time) are added to obtain surface soil heat flow, as follows:

g1 = shf1 + ces1,

etc.,

where shf1 and ces1 are, respectively, the soil heat flow from the soil heat flow plate and the change in energy storage measured from the soil temperature probe of soil set #1. The expressions for g2, g3, g4, and g5 are similar. Soil moisture is used to adjust the measurements for soil thermal conductivity, which affects the calibrations of the sensors.

Surface soil heat flow is then

ave_shf = (g1 + g2 + g3 + g4 + g5)/5,

When data from one or more soil set(s) is incorrect, that soil set(s) can be eliminated and the average soil heat flow determined from the remaining sets.

The Bowen ratio is measured as the ratio of the gradients of temperature and vapor pressure (the latter calculated from RH and temperature) across two fixed heights within three meters of the surface.

The Bowen ratio (B = h/e) is computed on the basis of the gradients and the following computations are performed:

e = -(q + ave_shf)/(1 + B)

h = B * e

More detailed information on these and other equations can be obtained elsewhere, including from DavidCook at Argonne National Laboratory. A large manual provided by the manufacturer, REBS, Inc., describes the general theory, gives rather complete information on each type of sensor, and explains procedures for installation, operation, and maintenance.

7.3 Calibration

7.3.1 Theory

Standard calibration procedures are employed by the vendor(s) of the sensors and equipment used in the EBBR system when each EBBR unit is returned for recalibration, approximately every two years.

7.3.2 Procedures

Net Radiometer: Calibration is performed in a temperature-controlled, black-body cavity chamber against a transfer standard. The light source is a tungsten-halide lamp. The transfer standard was calibrated both in the temperature-controlled cavity chamber and by comparison to an Eppley precision pyranometer outdoors. Wind speed effects are also taken into consideration by ventilating the radiometers in the calibration chamber and outdoors. The transfer standard is traceable to NIST through the Eppley pyranometer using a shading technique. Shortwave and longwave calibrations are different, and so they are applied appropriately for daytime and nighttime conditions in the EBBR programming. The longwave calibration performed by REBS does not provide correct measurements under conditions of low effective sky temperatures (below about -30°C).

7.3.3 History

The EBBR systems are returned to REBS approximately every two years for calibration of all sensors and data logger equipment. Some of the calibrations are performed by REBS themselves, while some are performed by manufacturers of the equipment. For various reasons (the need to provide and calibrate spare sensors, frequent AEM failures, etc.) the time between recalibrations of EBBR units has sometimes been greater than two years; REBS is a small company and has little flexibility to reprioritize rapidly for individual customers.

7.4 Operation and Maintenance

7.4.1 User Manual

A user manual is available from REBS for the SEBS systems. One copy is kept at the SGP Central Facility, and the mentor keeps one copy.

7.4.2 Routine and Corrective Maintenance Documentation

SGP Site Operations (Site Ops) personnel maintain preventative maintenance, corrective maintenance, and engineering logs. Maintenance and system checks are performed in accordance with a set of procedures written by Site Ops and the mentor. These procedures are maintained in print form at the SGP Central Facility and in digital form on Site Ops laptops taken into the field during preventative maintenance visits to the EBBR systems.

7.4.3 Software Documentation

EBBR programs are maintained on SGP Site Ops computers at the SGP Central Facility, on laptops used by Site Ops during preventative maintenance visits, and at REBS. The mentor maintains print copies and some digital copies.

7.4.4 Additional Documentation

Six-month EBBR checks are maintained on the SGP Operations Management Information System (OMIS) website.

7.5 Glossary

Bowen Ratio: the ratio of the sensible heat flux to the latent heat flux.

Latent Heat Flux: the transfer of latent heat (heat released or absorbed by water) between the surface and the air, or vice versa.

Net Radiation: the net difference in downwelling and upwelling solar plus terrestrial radiation.

Sensible Heat Flux: the transfer of sensible heat (enthalpy) between the surface and the air, or viceversa.

Soil Heat Flow: the transfer of sensible heat (enthalpy) in the soil, towards the surface or away from thesurface.

7.6 Acronyms

AEM	Automatic Exchange Mechanism
AERI	Atmospheric Emitted Radiance Interferometer
ARM	Atmospheric Radiation Measurement
BA	Bulk Aerodynamic Technique
DQ Explorer	Data Quality Explorer
DQO	Data Quality Office
DQR	Data Quality Report
EBBR	Energy Balance Bowen Ratio
ECMWF	European Centre for Medium-Range Weather Forecasts
ECOR	Eddy Correlation System
FIFE	First ISLSCP Field Experiment
GCIP	GEWEX Continental-Scale International Project
IMMS	Instrument Mentor Monthly Summary
IRT	infrared thermometer
MET	Surface Meteorological Instrumentation
NIST	National Institute of Standards and Technology
OMIS	Operations Management Information System
PILPS	Project for Intercomparison of Land-surface Schemes
PRTD	Platinum Resistance Temperature Detector
QC	quality control
QME	Quality Measurement Experiment
RH	relative humidity
RMSE	root-mean-square error
SEBS	Surface Energy Balance System
SGP	Southern Great Plains
SIRS	Solar and Infrared Station (Broadband Radiometers)
SWATS	soil water and temperature system
VAP	value-added product

Also see the [ARM Acronyms and Abbreviations](#).

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