Bulk Aerodynamic Energy Balance Bowen Ratio Value Added Product Corrections and Energy Balance Bowen Ratio CR10 Program Improvements

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Introduction

The Atmospheric Radiation Measurement (ARM) Program's energy balance Bowen ratio (EBBR) system estimates vertical fluxes of sensible and latent heat from vertical gradients of temperature and relative humidity, soil heat storage and transfer, and net radiation. Over the past 12 years of measurements, many changes and improvements have been made to the physical system and measurement methodology. However, it was recently recognized that more changes would be beneficial. Algorithms have been added to the EBBR CR10 datalogger program to reduce the significant frequency of incorrect sensible and latent heat flux estimates that result from malfunctioning soil sensors. Tighter rejection limits have been set on soil surface heat flux, net radiation, and Automatic Exchange Mechanism (AEM) home signals. The expansion of the datalogger program to accommodate these changes required an upgrade of the datalogger program memory. Furthermore, changes to the Bulk Aerodynamic (BA) EBBR Value-Added Product (VAP) are required to produce correct bulk aerodynamic calculations of sensible and latent heat fluxes. This is an alternative estimation scheme used to replace incorrect EBBR sensible and latent heat flux estimates that result from the Bowen ratio being near -1. All of the above changes are designed to improve the EBBR system data quality.

CR10 Datalogger Program Improvements

The present EBBR CR10 datalogger program does not perform any outlier checks. Therefore, outliers, particularly of Q (net radiation) or G (average soil heat flow), can cause the estimates of H (sensible heat flux) and E (latent heat flux) to be incorrect. The program has been modified and tested to reduce the frequency of these problems. Outliers of G, Q, and AEM home signals will cause sensible and latent heat flux to be converted to 9999.0 values by the new datalogger program.

The EBBR system uses five sets of soil sensors to determine G. Each set is composed of three sensors: a soil heat flow plate at 5 cm, a soil moisture probe at 2.5 cm, and a soil temperature probe at 0-5 cm (integrated temperature through the 0-5 cm column of soil). The problems that one incorrect soil measurement can cause can be seen from the equations governing the calculation of G.

The energy balance equation is Q + G + H + E = 0, with G calculated from the individual soil set heat flows as G = G1 + G2 + G3 + G4 + G5, where G1 through G5 are the individual soil set heat flows. When one or more of the soil sets provides an incorrect soil heat flow, G is incorrect.

A root mean square (RMS) rejection routine has been added to the CR10 datalogger program to remove outlier soil heat flows. First, G1 through G5 are checked for outliers using the acceptable range -200 to 100 Wm^{-2}. Next, the acceptable values are averaged (a new G). Each acceptable value is squared, these values are summed, the square root of the sum is taken, and the resulting value is divided by 2.2. The empirical value of 2.2 was calculated from a large amount of EBBR data. The maximum acceptable limit is defined by adding the result of this procedure to the average of the acceptable soil heat flows and the minimum acceptable limit is defined by subtracting the result of this procedure from the average of the acceptable soil heat flows (the equations below show all Gs as being used, which may not be the case):

$$\text{Maximum limit} = G + (G12 + G22 + G32 + G42 + G52)^{0.5}/2.2$$
$$\text{Minimum limit} = G - (G12 + G22 + G32 + G42 + G52)^{0.5}/2.2$$

Individual soil heat flows outside these limits are removed and G is re-calculated. Occasionally, the procedure removes correct values, but this typically occurs only when the soil heat flows are quite small, resulting in insignificant error.

Lastly, range limits for G, Q, and AEM home signals have been defined in the CR10 datalogger program. If G, Q, or AEM home signals are out-of-range, H and E are set to 9999.0. The limit check on G is performed despite the rejection scheme having been used, as a reasonable precaution. The limits used in the programming are shown below:

Q: -120 to 900 $W\ m^{-2}$
G: -200 to 100 $W\ m^{-2}$

Home Signal (hom_15, hom_30): reject if hom_15 or hom_30 are < 3;
reject if hom_15 minus hom_30 is < 10 (unless both are 60 to 90).

Other out-of-range home signals are normally the result of low battery voltage and thus incorrect H and E resulting from this condition can be detected from the ingest home signal quality control checks.

Bulk Aerodynamic Energy Balance Bowen Ratio Value-Added Product

An EBBR Bowen ratio (B) near -1 produces spikes in the observed H and E. The phrase (1 + B) in the equation for E (below) shows the root of the problem. When B is near -1, the denominator is very small and thus E and H become very large (in the absolute sense).

$$E = -(Q + G)/(1 + B)$$
$$H = B * E$$

The spikes usually occur during stability transition conditions, normally near sunrise or sunset, when the gradients of temperature and vapor pressure are small and of opposite sign. This is clearly shown in Figure 1 (e is latent heat flux; h is sensible heat flux) from E15, Ringwood, Oklahoma, when the Bowen ratio is -0.95 and -1.05. To overcome this "spike" problem, a bulk aerodynamic algorithm was implemented (in the BA EBBR VAP) to provide another estimate of the fluxes (ae and ah in the baebbr datastream); see Figures 2 and 3. Furthermore, the spikes in the measured EBBR fluxes are replaced by bulk aerodynamic sensible and latent heat fluxes (in the BA EBBR VAP) to create a "combined" set of sensible and latent heat fluxes (ecomb and hcomb in the baebbr datastream), better known as the "best estimate" fluxes (see Figure 4).

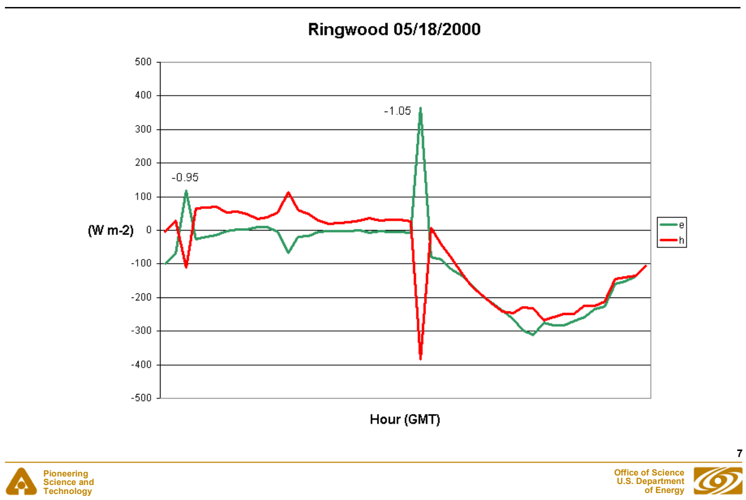

Figure 1. Spikes in fluxes from Bowen ratio near -1.

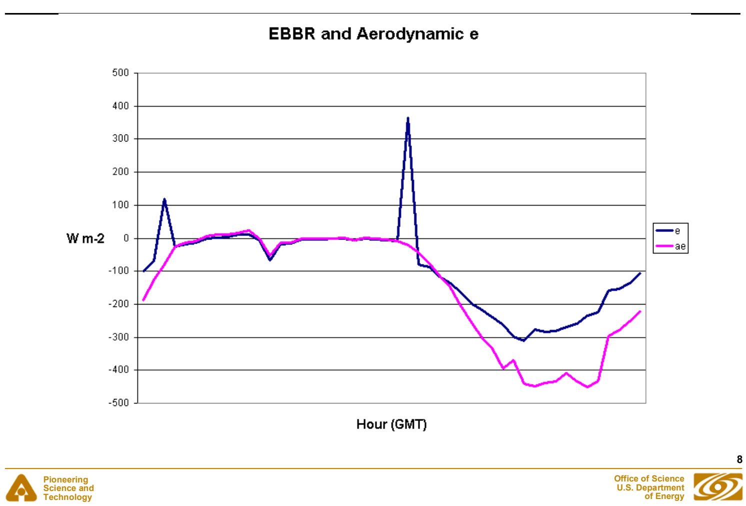

Figure 2. Aerodynamic latent heat flux ae compared to measured e.

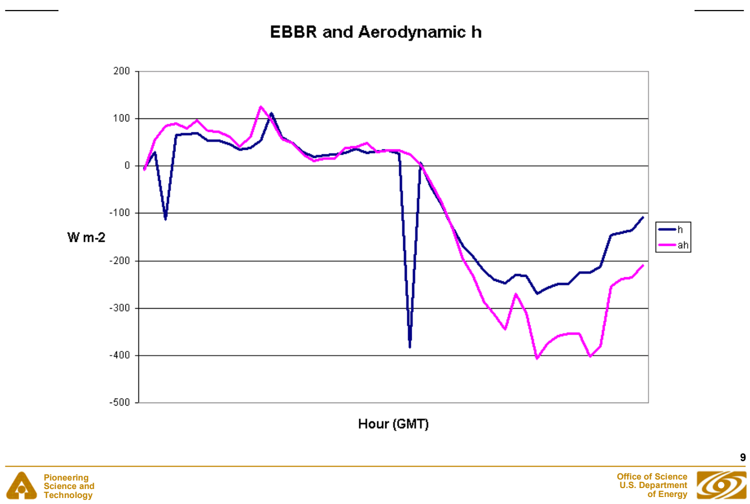

Figure 3. Aerodynamic sensible heat Flux ah compared to measured h.

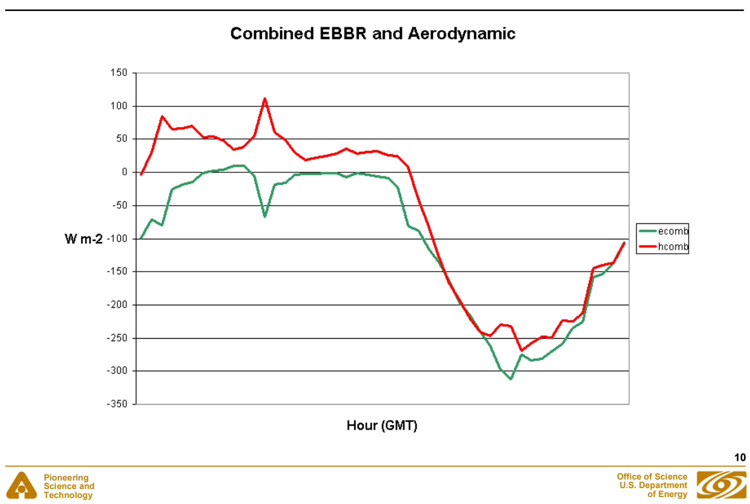

Figure 4. Combined set, latent heat flux ecomb; sensible heat flux hcomb.

Bulk Aerodynamic Energy Balance Bowen Ratio Value-Added Product Corrections

The following corrections to the BA EBBR VAP programming are needed.

- Clean up some comment lines.
- Insert a missing statement.
- Tighten min/max limits on net radiation, and sensible and latent heat fluxes.
- Expand the “spike” Bowen ratio range.
- Use correct sensor heights.

The last two items are the most critical and affect the quality of the BA EBBR VAP calculations.

Some of the comment lines in the BA EBBR VAP aero.c program need to be cleaned up to make them more readable. The details of this are not presented here.

A statement setting a minimum value for sensible heat flux is missing in aero.c and needs to be added.

The present and tightened (in parentheses) min/max limits on net radiation are shown below, as well as appropriate limits for sensible heat flux and latent heat flux (if these are used in programming that calls the BA aero.c program). The net radiation maximum is currently so large that the program would not reject net radiation data for the situation where there is water in the bottom dome of the net radiometer.

Q: -500 to 1500 (-120 to 1000) W m^{-2}

H and E: -1000 to 200 W m^{-2}

Expanded “Spike” Bowen Ratio Range

The BA EBBR VAP currently uses a Bowen ratio replacement range of -1.5 to -0.75. However, analyses of the EBBR data show that the range needs to be expanded to -1.6 to -0.45. Figures 5 and 6 demonstrate this. Note the deviations from the EBBR measured fluxes at Bowen ratios of -0.643, -1.588, and -0.48. Using the expanded range will smooth the combined set sensible and latent heat fluxes for Bowen ratios near -1.

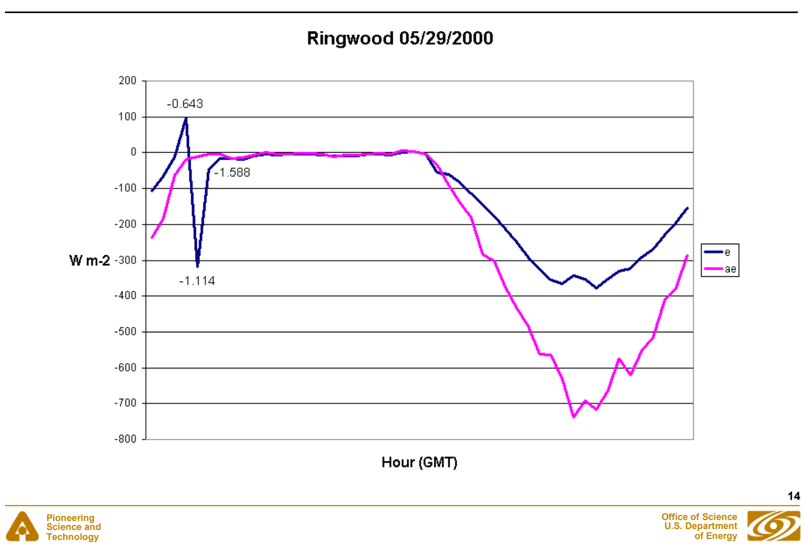

Figure 5. EBBR data spikes for Bowen ratios of -0.643 and -1.588 (outside the present replacement range).

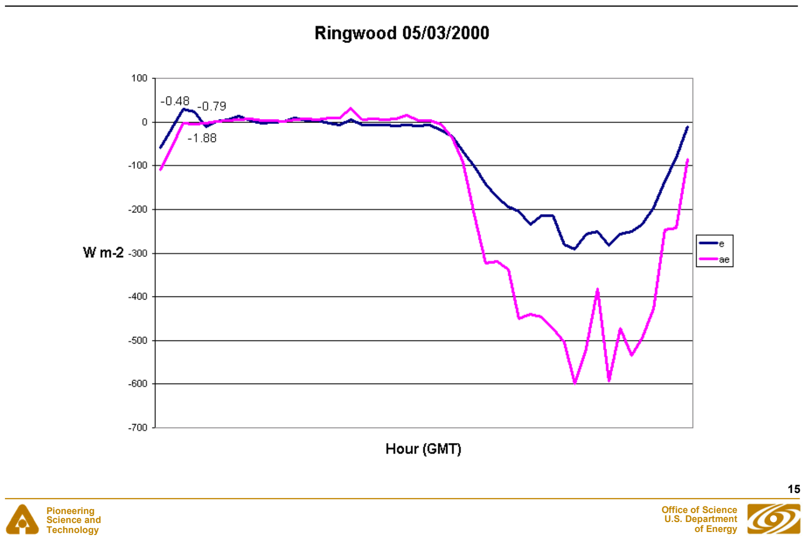

Figure 6. EBBR data spikes for Bowen ratios of -0.48 and -1.88 (outside the present replacement range).

Correction of Sensor Heights in Bulk Aerodynmic Energy Balance Bowen Ratio Value-Added Product

Figures 5 and 6 show that the bulk aerodynamic calculations of fluxes are considerably larger (in the absolute sense) than the measured EBBR fluxes during daylight hours. This is caused by the use of fixed sensor heights (1.9 m and 0.9 m for top and bottom AEM heights, respectively, and 3.4 m for wind speed height), instead of site specific heights, in the BA EBBR VAP programming. The actual range of AEM top heights is 1.61 to 2.93 m and the actual range of wind speed sensor heights is 2.8 to 3.4 m. The AEM heights have varied over the years of measurements, depending on vegetation height; the wind speed heights have not changed. The AEM heights are now fixed at an appropriate height at each site and are not to be changed.

The bulk aerodynamic technique flux calculations are proportional to and quite sensitive to the natural log of the ratio of AEM top height and bottom height and the ratio of wind speed sensor height and roughness length (flux ~ $1/[\ln(z_2/z_1)\ \ln(z_u/z_0)]$).

The second log ratio is used in the calculation of u* (friction velocity):

u* = k u / [ln(zu/zo) – fim]

where

k = ~0.38 (Von Karman constant)
u = wind speed
d ~ vegetation height * 0.66 (displacement height)
z_u = wind speed sensor height – d

z_0 ~ vegetation height / 0.75 (roughness length)
fim = momentum stability function.

The first log ratio is used in the H and E calculation equations:

H = - (ρ cp k u* dt)/(ln(z2/z1) - fih2 + fih1)
E = - (ρ Lv k u* de)/(ln(z2/z1) - fih2 + fih1) + air density corrections

where

ρ = air density
c_p = specific heat of air at constant pressure
L_v = latent of vaporization
d_t = top minus bottom temperature
de = top minus bottom vapor pressure
z_2 = top AEM height
z_1 = bottom AEM height
fih1 and fih2 = scalar stability functions.

The effect of fixed AEM heights in the BA EBBR VAP is seen from a list of sensible and latent heat flux errors at each of the 15 EBBR sites; the error values are based on the maximum vegetation height (Note: The errors may be less for shorter vegetation heights) and the present AEM heights (the AEM height used for E25 was the height at the time that the site was de-commissioned):

E2	-5
E4	-76
E7	+41
E8	+13
E9	-17
E12	-76
E13	-82
E15	+60
E18	-5
E19	-83
E20	-51
E22	-51
E25	-14
E26	-49
E27	-11

The large positive value for E15 explains the large overestimation of fluxes by the bulk aerodynamic technique, as displayed in Figures 2, 3, 5, and 6.

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