Objective Criteria for Rejecting Data for Bowen Ratio Flux Calculations

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ABSTRACT

In addition to the inherent problem of accumulating errors of measurement of net radiation and subsurface heat flux, the Bowen ratio energy balance method often produces totally unacceptable sensible and latent heat fluxes: wrong signs (directions) and extremely inaccurate magnitudes of the fluxes, or both. These problems are due to resolution limits of the instruments. Objective criteria to eliminate undesirable data are derived in general forms. An example is graphically presented for the common case of the psychometric tower with a 0.05°C resolution limit of temperature measurement.

1. Introduction

When Bowen (1926) proposed the flux ratio which is now called the Bowen ratio, he did not mention any possible problems except the dissimilarity of the eddy diffusivities. Estimations of the flux errors calculated using the Bowen ratio energy balance method were subsequently presented by Fritschen (1965), Fuchs and Tanner (1970) and Blad and Rosenberg (1974). Due to the resolution limits of the instruments, however, the Bowen ratio method may result in very inaccurate flux calculations. Such cases are unfortunately not limited only to the hours of small flux values, as is often assumed. To prevent the acceptance of physically inconsistent or extremely inaccurate flux values, a rejection scheme for inappropriate data is necessary. A simple yet general data rejection program was developed and is at present successfully applied to the routine processing of tower data in the author's institute.

2. Identification and causes of the problem

The original definition of the Bowen ratio was made with respect to fluxes as follows (Bowen, 1926):

$$\beta = H/LE,$$

where notations are defined in the Appendix.

The Bowen ratio is, however, often expressed after approximating the fluxes by gradients in the following manner

$$\beta = \frac{H}{LE} = \alpha \frac{c_p \Delta T}{L \Delta q}. \tag{1}$$

It is this form that is most often used to calculate sensible and latent heat flux upon combining the equation of surface energy balance:

$$R + H + LE + S = 0. \tag{2}$$

The sign of the energy fluxes is taken positive downward.

The only advantage of the Bowen ratio energy balance method is the capability for calculating turbulent fluxes without absolute values of the eddy diffusivities. There are three main problems, however.

a. Problem 1

The first problem is inherent in all energy balance methods: errors in the evaluation of net radiation and subsurface fluxes are accumulated in the evaluation of the turbulent fluxes. The error estimation of latent heat flux due to errors in net radiation, soil heat flux, and vertical temperature and vapor pressure differences, was described by Blad and Rosenberg (1974) in a form of the root-sum-square of the above four components. In practice, however, this error estimate can range from zero to infinity, because the signs of ΔT and Δe can be opposite. The author considers it more practical to design some criteria which pick out physically inconsistent results and cases of instrumental resolution limits. The most serious disadvantage in applying the Bowen ratio energy balance method is found for surfaces for which the estimation of subsurface energy flux is difficult. Such surfaces are water, which partially transmits shortwave radiation; melting snow cover, whose melting rate is difficult to determine; and porous layers, such as forest, whose rates of heat storage are also difficult to estimate. When the water body is in motion through a temperature gradient, the application of the Bowen ratio flux calculation becomes extremely difficult. Ironically, the first proposal of this method by Bowen (1926) was made for water.

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b. Problem 2

In addition to this first inherent problem, the Bowen ratio energy balance method is subject to more serious difficulties when applied in practice. The second problem is the possibility of obtaining wrong signs for the turbulent fluxes; for example, the confusion between evaporation and condensation. This problem can be formulated below. Eqs. (1) and (2) give the following well-known relation:

$$[1 + (\alpha c_p/L)(\Delta T/\Delta q)]LE + R + S = 0. \quad (3)$$

After rearrangement of Eq. (3) we have

$$\Delta q/E = -(L\Delta q + \alpha c_p \Delta T)/(R + S) < 0. \quad (4)$$

The inequality sign is justified regardless of how the coordinate system is taken, as the direction of the flux is always opposite to that of the gradient. This inequality can be rewritten for the following two conditions:

$$\left.\begin{array}{llll} \text{If} \quad R + S > 0 & \text{then} \quad L\Delta q + \alpha c_p \Delta T > 0 & \text{or} & \Delta T > -(L/\alpha c_p)\Delta q \\ \text{If} \quad R + S < 0 & \text{then} \quad L\Delta q + \alpha c_p \Delta T < 0 & \text{or} & \Delta T < -(L/\alpha c_p)\Delta q \end{array}\right\}. \quad (5)$$

If the data do not satisfy one of these conditions, the flux calculation with the Bowen ratio gives a flux direction the same as that of the gradient, although the absolute magnitude might be correct. Such a situation is not consistent with the definition of the flux/gradient relationship and the data should be excluded from the calculation.

A common case of the second problem is a positive value of the calculated latent heat flux, i.e., condensation, while the gradient of specific humidity is positive, suggesting evaporation, which should give a negative flux. For this type of error all the errors in net radiation, subsurface heat flux and the temperature and humidity profiles are responsible. Improperly adjusted temperature and humidity profiles due to the inhomogeneity of the surface and the nonsteady state can also cause this problem. The author often encountered this problem with early morning and late afternoon data and during precipitation, when gradients were small, the boundary layer was not in a steady state, or the net radiation and subsurface heat flux were not accurately measured.

An example of this problem is presented in Table 1. 4 June 1970 was a typical radiation day in the late premelt period in the region of the base camp on Axel Heiberg Island, Northwest Territories, Canada. The data for 0600 TST fall into the category to be rejected, because they do not satisfy either of the inequalities in (5). This is the hour when the early morning flip of the heat fluxes took place. The problem in this particular case was subsequently found to be due to an overestimation of subsurface heat flux, which resulted from an overestimation of the heat absorbed by the snow cover.

c. Problem 3

The third problem is the possibility of obtaining an extremely inaccurate magnitude of the fluxes, even though signs are correct. This problem is illustrated in the following equation which expresses latent heat flux by the Bowen ratio

$$LE = -(R + S)/[1 + (\alpha c_p/L)(\Delta T/\Delta q)]. \quad (6)$$

When the Bowen ratio approaches -1, although it may not be exactly -1, the value of LE loses its numerical meaning. This problem is also inherent in the Bowen ratio energy balance method, and even without errors of measurement, the application of this method becomes impossible when the Bowen ratio becomes exactly -1. This is the condition prevailing on the surface of the wet bulb of a psychrometer. In nature, however, this condition is rarely found. It was, nevertheless, often found that the results were obviously inaccurate, such as $LE = -9550$ W m^{-2} and $H = 9600$ W m^{-2}. This situation is caused by a Bowen ratio which is very close to -1. Under such a condition, even a minute error in net radiation or subsurface heat flux would cause an unacceptable result. The hours showing this type of problem are early morning, late afternoon, during precipitation and especially during an intense foehn wind, when the direction of latent heat flux is opposite that of sensible heat flux. The problem under the foehn is very serious because evaporation is usually large.

It is necessary to judge if the results of the Bowen ratio flux calculation are sufficiently close to reality, or rather faulty due to the error of measurement and the resolution limits of the instrumentation. The criterion for rejecting data with this problem is formulated below.

With the resolution limits of the thermometers and hygrometers being $E(T)$ and $E(q)$, respectively, the relationship between the true temperature difference δT and the observed temperature difference ΔT is

$$\Delta T - 2E(T) < \delta T < \Delta T + 2E(T). \quad (7)$$

Similarly, for specific humidity,

$$\Delta q - 2E(q) < \delta q < \Delta q + 2E(q). \quad (8)$$

From these inequalities the following relation can be justified:

$$\alpha c_p[\Delta T - 2E(T)] + L[\Delta q - 2E(q)] < \alpha c_p \delta T + L\delta q < \alpha c_p[\Delta T + 2E(T)] + L[\Delta q + 2E(q)]. \quad (9)$$

When the Bowen ratio is -1, $\alpha c_p \delta T + L\delta q = 0$, and

TABLE 1. An example of wrong signs for turbulent fluxes calculated by the Bowen ratio energy balance method. Station: Base Camp, McGill University Axel Heiberg Island Expedition, N. W. T., Canada. Date: 4 June 1970.

Time in TST (1 h starting)	Net radiation (W m^{-2})	Subsurface heat flux (W m^{-2})	Latent heat flux (W m^{-2})	Sensible heat flux (W m^{-2})	Air temperature (°C)		Specific humidity (g kg^{-1})		Bowen ratio	Remarks
					150 cm	20 cm	150 cm	20 cm		
04	18	7	−8 (−6)*	−17 (−15)	−8.56	−7.72	1.86	1.99	2.26	accepted
05	15	3	−6 (−4)	−13 (−9)	−8.43	−7.92	1.88	1.96	2.26	accepted
06	17	−23	2 (−4)	5 (−10)	−8.09	−7.52	1.93	2.02	2.25	rejected
07	30	−15	−6 (−6)	−9 (−15)	−7.22	−6.18	2.11	2.34	1.61	accepted
08	40	−22	−7 (−8)	−10 (−13)	−8.02	−7.19	1.94	2.12	1.63	accepted
09	31	−16	−6 (−6)	−9 (−9)	−7.76	−7.12	1.98	2.13	1.62	accepted

* Turbulent fluxes in parentheses are calculated values based on the gradient/flux relationship proposed by Panofsky *et al.* (1960).

relation (9) becomes

$$-(L/\alpha c_p)\Delta q - 2[(L/\alpha c_p)E(q) + E(T)] < \Delta T < -(L/\alpha c_p)\Delta q + 2[(L/\alpha c_p)E(q) + E(T)]. \quad (10)$$

If the above inequality is satisfied, there is a high possibility that the Bowen ratio will be very near −1 and the calculated flux will not possess numerical meaning. Therefore, such data should be excluded from evaluation.

An example of the problem for a case under intense foehn conditions is presented in Table 2. The data for 0700, 0800 and 1000 TST are rejected because their ΔT and Δq satisfy inequality (10). Although the data for 0800 LST do not produce $\beta \simeq -1$, they come very close to the straight line $\alpha c_p \Delta T + L\Delta q = 0$, due to the small absolute values of ΔT and Δq. The data for 0600 and 0900 LST are rejected by the criterion already discussed with respect to Table 1. The example presented in Table 2 represents an energy balance under the foehn on the west coast of Axel Heiberg Island. Variable cloud and wind conditions caused a high-frequency unsteady condition. Despite large insolation, the foehn air remained warmer than the surface. There was a continuous sensible heat flow from the atmosphere to the surface, while evaporation frequently took place. This condition is most unsuitable for the evaporation measurement based on the Bowen ratio energy balance method.

Inequalities (5) and (10) were evaluated for a psychrometric system with a 0.05°C limit of temperature resolution and air temperature near 0°C. The region of data rejection for such an instrument is graphically presented in Fig. (1). These relations are easy to program and can be used to routinely check doubtful data.

3. Conclusion

Due to one-dimensional steady-state assumptions in the Bowen ratio energy balance method, and the resolution limits of the instruments, the use of gradients of temperature and specific humidity for the evaporation calculation is not always justified. The Bowen ratio energy balance method requires certain rejection criteria for inappropriate data. Such criteria are formulated from the viewpoint of physical inconsistency of the flux/gradient definition and resolution limits of the instruments. After applying this

TABLE 2. An example of erroneously large absolute values for turbulent fluxes calculated by the Bowen ratio energy balance method. Station: Base Camp, McGill University Axel Heiberg Island Expedition, N. W. T., Canada. Date: 31 May 1970.

Time in TST (1 h starting)	Net radiation (W m^{-2})	Subsurface heat flux (W m^{-2})	Latent heat flux (W m^{-2})	Sensible heat flux (W m^{-2})	Air temperature (°C)		Specific humidity (g kg^{-1})		Bowen ratio	Remarks
					150 cm	20 cm	150 cm	20 cm		
06	41	−51	−1 (10)*	−16 (14)	−2.19	−3.33	2.88	2.85	12.73	rejected
07	80	−80	27 (−3)	−80 (9)	−1.73	−2.26	3.07	3.14	−2.95	rejected
08	52	−58	−2 (1)	−28 (12)	−2.43	−2.93	3.02	3.01	11.52	rejected
09	47	−70	−3 (6)	−15 (28)	−2.09	−2.96	3.04	2.97	4.31	rejected
10	65	−52	−143 (−19)	108 (14)	−1.93	−2.29	3.02	3.20	−0.76	rejected
11	64	−47	−39 (23)	3 (2)	−1.66	−1.69	3.16	3.32	−0.07	accepted

* Turbulent fluxes in parentheses are calculated values based on the gradient/flux relationship proposed by Panofsky *et al.* (1960).

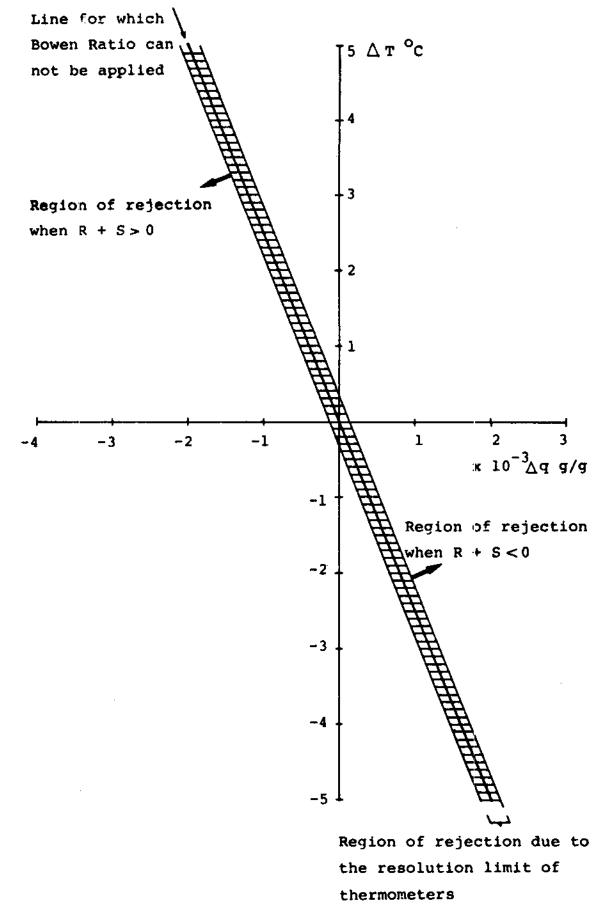

FIG. 1. Criteria for rejection of the gradient data for the Bowen ratio flux calculations for psychrometric towers, with limit of thermometer resolution of 0.05°C and air temperature near 0°C. R is net radiation; S subsurface heat flux; and ΔT and Δq temperature and specific humidity differences observed at two levels, respectively.

method to field data, it was found that the data for early morning, late afternoon and during precipitation often had to be rejected. The effect of the missing data for these periods may not be serious for the total evaporation for a period longer than a day, because evaporation rates are usually small. The rejection criteria, however, often picked-up undesirable data for the period of intense foehn. Since evaporation rate under foehn conditions is usually large, this problem should be seriously considered for foehn-affected regions and particularly for the Alpine Experiment (ALPEX) instrumentation.

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APPENDIX

Definitions of Symbols

c_p	specific heat of air at constant pressure
E	evaporation rate
$E(q)$	limit of resolution for a hygrometer
$E(T)$	limit of resolution for a thermometer
H	sensible heat flux
K_h	eddy diffusivity for sensible heat
K_w	eddy diffusivity for water vapor
L	latent heat of vaporization
δq	difference in specific humidity between two levels
Δq	observed value of δq
R	net radiation
S	subsurface heat flux
δT	difference in air temperature between two levels
ΔT	observed value of δT
α	K_h/K_w
β	Bowen ratio

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