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# Direct measurement of evaporation from grassland at Plynlimon

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## Abstract

Over the last decade there has been some uncertainty over the calculation of 'actual' catchment evaporation from the long-term difference between rainfall and runoff for the grassland Wye catchment at Plynlimon, compared to estimates made using the Penman formula on data from automatic weather stations. Hence, measurements of actual evaporation were made over a two month period in the late summer of 1992 using the eddy-correlation technique on a relatively flat but wetter than average site in this upland region. Although the site was rather restricted for this type of measurement, the quality of data proved typical of other eddy-correlation measurements made at more aerodynamically suitable sites. The ratio of actual evaporation to the Penman estimate on dry days in summer was 0.83. This compares with an average annual ratio, generated from the catchment data for the period 1978 to 1995, of 1.01. The catchment rainfall value has been improved recently by weighting each gauge using altitude domains.

## Introduction

Examination of the first nineteen years' of data (1969 to 1987) from the grassland Wye catchment in Plynlimon, mid-Wales (Hudson and Gilman 1993), revealed a suspected discrepancy in the water balance calculations, although the percentage errors are compounded by taking the difference between the two relatively large values of rainfall and runoff. This has recently been resolved with an improved rainfall catchment value by weighting each gauge using altitude domains. Of the data presented by Hudson and Gilman (1993) those from the last ten years (1978 to 1987) are regarded as more reliable as instrument problems were overcome and data collection was automated. During this period, the average ratio of the difference between annual rainfall and runoff to the Penman estimate of evaporation, calculated from automatic weather station data, now averages 0.95 with 0.15 S.D. Actual annual evaporation thus calculated averages only 26 mm less than the Penman estimate (with 82 mm S.D.). With mean annual rainfall of 2610 mm well distributed over the year, the grass should be plentifully supplied with water for most of the time. This study has since been extended to 1995 with the above ratio becoming 1.01 with 0.15 S.D. for the period 1978 to 1995. This paper describes a short study to *measure* the evaporation directly and compare it with *estimates* made with the Penman formula, as opposed to calculating it from the long term difference between rainfall and runoff. The instruments used were an Automatic Weather Station (AWS) (Didcot Instrument Company, Abingdon, UK.) and a Hydra eddy-correlation device made by the Institute of Hydrology (Shuttleworth *et al*, 1988). This latter instrument calculates hourly measurements of evaporation by monitoring the flux of water vapour through the turbulent atmospheric boundary layer close to the surface.

## Site and Instrumentation

The Hydra is a one dimensional instrument with a single, vertical sonic anemometer. The eddy-correlation method requires that such an instrument be mounted perpendicular to the streamlines of wind. While this criterion can be fulfilled on level or uniformly sloping sites, for complex undulating terrain this is impossible, as the required mounting angle will vary with wind direction. Suitable flat sites are rare in upland regions such as Plynlimon. However, one site was located on top of a grass ridge aligned along a bearing of 70° from north, just outside the grassland Wye catchment and adjacent to the forested Severn catchment, at 3° 40' 34" west, 52° 27' 48" north (Fig. 1). The streamlines of the predominantly south-west winds are therefore approximately horizontal and perpendicular to the Hydra. Unfortunately, the site is poorly drained with deep peat soils and is therefore wetter than most of the catchment. During installation at the end of July, the ground surface was wet even after four dry days. However, the site fulfils Penman's criterion of 'grass plentifully supplied with water' and should therefore be evaporating at full potential rate. Most of the rest of the catchment is sloping and drier with much thinner soils from which the water runs off more quickly. The area on the ridge chosen had vegetation similar to that on most of the slopes.

The most unsuitable fetches were between 20° and 160° from north. Between 20° and 110°, there is a large grassed scoured area surrounded by up to two metre cliffs of peat. Between 110° and 160°, the ground falls away gently to a lush marsh, with minor scouring and marshy areas in front. The Hydra was pointed away from these areas, pointing due west, with the AWS a few metres to the east. Between 250° and 340° the ground sloped away most steeply from the site and contained an area of scouring that was free of vegetation. There was a reasonable but short fetch of approximately 150 metres, ± 20° of north, over the highest point of the ridge before dropping down a steep slope. The best fetch of at least 250 metres was from 160° through to 250° from north. Together, the directions within these two fetches contained 65 per cent of the daily average wind directions recorded at the site during the measurement period. Trees grow east of the site (Fig. 1) within directions of 55° and 110° from north at a distance of about 700 metres.

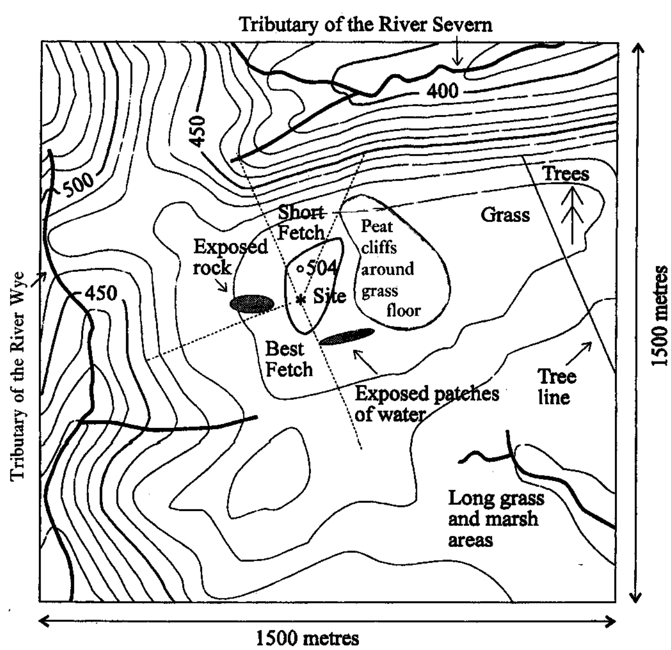


Fig. 1. *Map of the area surrounding the site.*

Data were collected between 30 July and 7 October 1992, using a Hydra with a Radiation and Energy Balance Systems Q*6 net radiometer and an AWS with a Sauberer and Dirmhirn type net radiometer. The Hydra contains a fast response optical hygrometer that monitors changes in the absorption of infra-red light by water vapour. Rain or dew in the optical path or on the lenses swamp the signal completely. The Hydra is, thus, a fair weather instrument and siting it at Plynlimon, where it rains on almost 75% of days (anything up to 50 mm per day during this measurement period), inevitably means that data retrieval was limited to the few dry days which occurred. The equipment was surrounded by a three wire electric fence to keep out deer etc. and no farm animals grazed the site.

## Results and Discussion

In assessing evaporation from the Wye catchment (Hudson and Gilman, 1993), the Penman (1948) estimate of evaporation was calculated as a daily value from air temperature, wet bulb depression, net radiation and wind speed using the data collected by two AWS, one at the west end of the catchment at 500m elevation and one at the outlet of the Wye from the southern end of the catchment at 350m elevation. More recently (Hudson *et al*, 1997), a factor of 1.31 has been established (1992 to 1995) between the Penman estimate of evaporation calculated by these two stations and that from the manual weather station at Moel Cynnedd on the Severn catchment. This factor has been used to infill missing data periods of the Wye stations. The average annual Penman estimate of evaporation for the two periods 1978 to 1987 and 1978 to 1995, calculated by the two Wye stations is identical to that of the Moel Cynnedd station with adjustment by this factor. Although physically based, the Penman equation contains empirical constants generated from an experiment using short lush grass plentifully supplied with water (Penman, 1948). If the leaf area index is much smaller than in Penman's experiment, or if there are biological controls on leaf transpiration in response either to soil water depletion or to atmospheric conditions, then this estimate may be too large. On the other hand, if the grass is longer than in Penman's experiment, it will evaporate more as a result of it having a rougher surface and intercepting more rain.

For the sixteen days when rain or dew did not affect the Hydra more than could reasonably be dealt with by interpolation over particular hours of missing data (see below), the average value of the Penman estimate calculated from the AWS at the experimental site was 2.34 mm with 0.9 mm S.D. per day. The ratio of the measured daily evaporation using the Hydra to the Penman estimate at the site (the E/PE ratio, Fig. 2) was 0.83 with 0.09 S.D.. The days with the wind blowing over the short fetch to the North were too wet to use.

## Interpolation of Missing Data

Interpolation of the data to compensate for missing values was essential at this site; otherwise only three complete days would have been available for use. When the infrared hygrometer was wet from rain during the night or from early morning dew, then the evaporation for these hours was assumed to average out to zero. As dew forms, the evaporation is negative. It is then positive as it re-

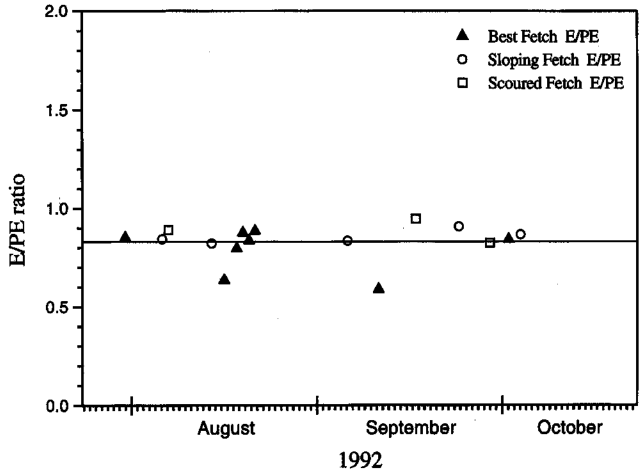


Fig. 2. *Ratio of measured to estimated evaporation with the predominant daytime fetch.*

evaporates, giving a net evaporation of zero. In the event of a short shower during the day, the evaporation value was interpolated or estimated from adjacent or nearby hours, scaled according to the net radiation. On average, 4 hours of data were interpolated per day. On four of the sixteen days it was considered possible to obtain a useful result by interpolating more than four hours of data.

## Error Analysis

A useful measure of the confidence which can be placed on the evaporation measured by the Hydra is to compare the total outgoing energy from the surface with the available incoming energy. This is done via the recovery ratio, which is defined as the ratio of the measured outgoing evaporation plus sensible heat flux to the net radiation less the soil heat flux.

Because daily evaporation and sensible heat flux are both measured by the Hydra whilst the AWS measures daily net radiation and soil heat flux (3.4% with 1.4% S.D. of the net radiation), the denominator and numerator of the recovery ratio are measured independently.

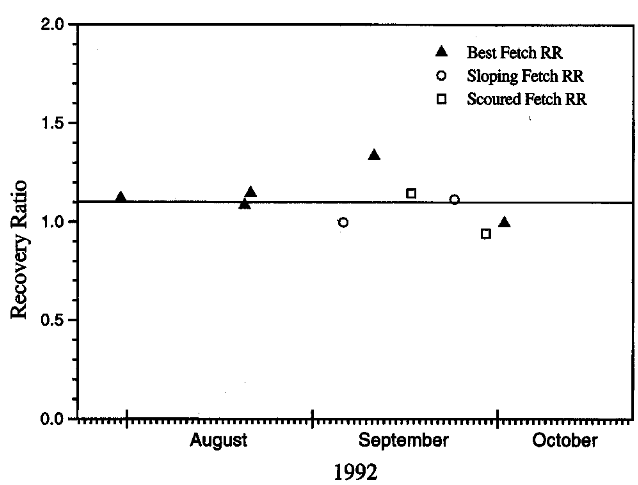


Fig. 3. *Recovery ratio with predominant daytime fetch.*

Between the 5 and 19 August, the fine wire thermocouple, used in the calculation of the sensible heat flux, was broken. This left only nine usable days when both the sensible heat flux and evaporation measurements were available to calculate a recovery ratio. These are shown in Fig. 3 giving an average value of 1.10 with 0.12 S.D.

Some of the day-to-day variability is probably caused by the radiation and soil heat flux terms being measured at a point, while the fluxes measured by the Hydra are an upwind bulk average. The average ratio is slightly above one, though not excessively so compared with other eddy-correlation experiments (Shuttleworth *et al.*, 1988). Interestingly, the highest recovery ratio was obtained on the day with the highest windspeed (average 8.7 m $sec^{-1}$, Fig. 4) even though the E/PE ratio was the lowest on that same day.

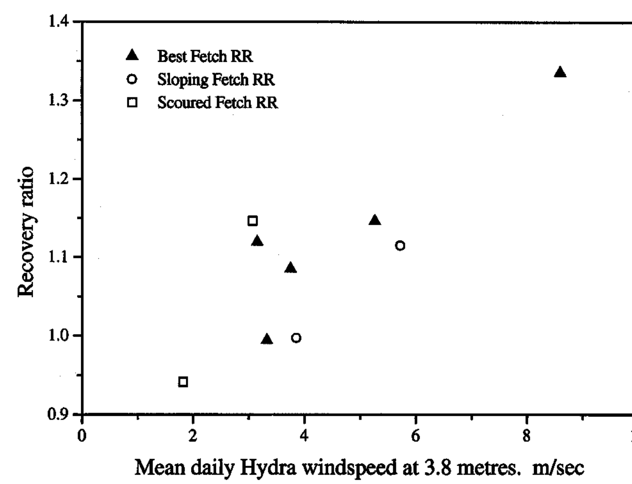


Fig. 4. *Recovery ratio versus windspeed with the predominant daytime fetch.*

However plotting the residual (evaporation + sensible heat flux + soil heat flux − net radiation) shows that the error is not proportional to windspeed (Fig. 5).

The effect of the wind on the recovery ratio has been seen in other studies using the Hydra and it may be that wind induced vibration causes a spurious enhancement to the variances of humidity in some of the instruments, thus increasing the evaporation signal. This would increase the recovery ratio most on low net radiation days as was the case for the highest windspeed day in this study. Destruction of momentum in the air flow at the ground surface may well produce only a negligible amount of energy to enhance evaporation.

It could be argued that a recovery ratio significantly different from unity casts doubts on whether the site was acceptable from the point of view of the streamlines being on average perpendicular to the one dimensional sonic anemometer. This was investigated by comparing the ratio

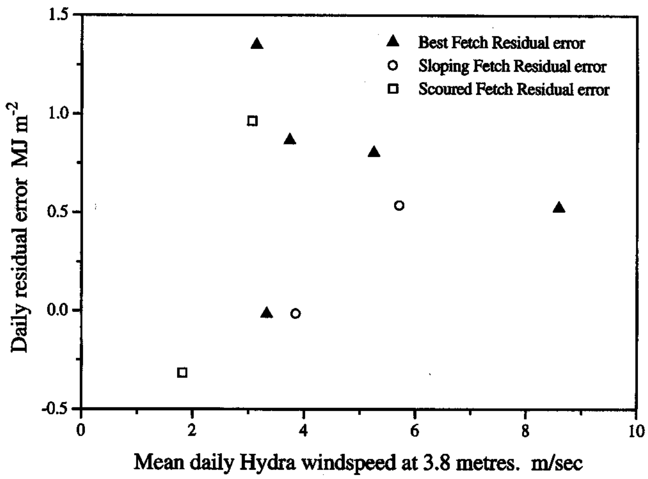


Fig. 5. *Residual error versus windspeed with predominant daytime fetch.*

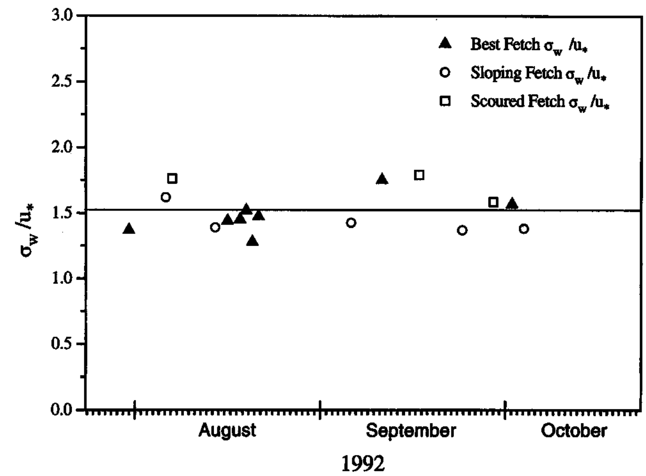


Fig. 6. *Daily average values of $\sigma_w/u_*$ with predominant daytime fetch.*

of the variances in vertical wind speed, $\sigma_W$, to the friction velocity, $u_*$ (the averaged square root of the product of the horizontal and vertical windspeed fluctuations). Under conditions of neutral stability, this ratio should have a value of approximately 1.3 (Panofsky and Dutton, 1984). If the streamlines are not perpendicular to the instrument, the measured vertical velocity will contain a component of the horizontal velocity and raise the ratio above its expected value. Upwind obstructions or interference by the frame of the instrument will also cause $\sigma_W/u_*$ to deviate from its neutral stability value.

In the vast majority of cases, the atmospheric stability conditions observed were neutral. The high winds, resulting in well mixed air, minimise the occurrence of unstable thermal buoyancy as well as of stable inversion conditions. The average daily $\sigma_W/u_*$ ratio is plotted in Fig. 6. Night time data were omitted, as wild excursions were common and night time water vapour fluxes are small compared with those in the daytime. The data were also restricted to dry hours, as rain affected the sonic anemometer, though to a much lesser extent than the optical hygrometer.

The average value of $\sigma_w/u_*$ was found to be 1.51 with 0.15 S.D. (Fig. 6) although by not using the three scoured fetch days this value reduced to 1.47 with 0.12 S.D. (The majority of the daylight hourly data was also within the same band as the daily data although there were some wild excursions). This prompted a comparison with the value obtained at other sites. An open flat site near Oxford, which would be expected to conform to the accepted value of 1.3, was also found to have an average value of 1.5 using the same sensors. The similarity between values for $\sigma_w/u_*$ found for the Plynlimon site and the flat site suggest, therefore, that the high average value of $\sigma_w/u_*$ was caused mainly by the slow response of the cup anemometer and that the one dimensional sonic anemometer of the Hydra was mounted approximately perpendicular to the airstream most of the time and so there was little upwind disturbance, except possibly from the area where the peat had been scoured out. It is suspected that the high value of $\sigma_w/u_*$ was caused by the use of relatively heavy but robust plastic anemometer rotor cups, instead of the lighter, but more delicate, polystyrene cups that would normally be used in a study of turbulence. The plastic cups are used for long term installations especially in windy conditions but, being unable to respond fast enough to the fluctuations of windspeed, they reduce $u_*$ and thereby increase $\sigma_w/u_*$.

The 10 per cent excess in the recovery ratio (Fig. 3) from a value of unity is caused by a combination of errors in both the eddy-correlation and energy budget measurements. From experience, the evaporation component is more prone to error than the sensible heat component of the eddy-correlation energy measurement. This percentage error will therefore affect the recovery ratio more as the ratio of evaporation to sensible heat increases. In this case evaporation was, on average, twice the sensible heat flux. Although the soil heat flux measurement is very prone to error, it was only 3 per cent of net radiation, so is unlikely to be responsible for major energy budget errors.

If the eddy-correlation measurement of evaporation is too high, it will result in the E/PE ratio being overestimated. Alternatively, a recovery ratio of greater than unity could be caused by too low a measurement of net radiation. This would cause an underestimate of evaporation by the Penman formula and again result in the E/PE ratio being overestimated. So a recovery ratio of greater than unity suggests that the E/PE ratio is overestimated. Errors in the eddy-correlation measurement of evaporation would pass directly through to the E/PE ratio whereas the effect on the Penman estimate of errors in net radiation is slightly complicated by it being split into an energy term and an aerodynamic term. If all the 10 per cent discrepancy in energy closure is attributed to the AWS net radiation measurement, the average PE would increase by about 7 per cent and E/PE would decrease from 0.83 to 0.77. Errors in net radiometers have been discussed by Halldin *et al* (1992). An error of 1 MJ $m^{-2}$ $day^{-1}$ for this type of net radiometer (Sauberer-Dirmhirn) is fairly typical which would be 16 per cent of the average value measured in this study and include all but one of the residual error points in Fig. 5. This radiometer was compared with a Radiation and Energy Balance Systems Fritschen type Q*6 net radiometer (assessed (Halldin *et al* 1992) to have a typical error of 0.6 MJ $m^{-2}$ $day^{-1}$) at the same site. Unfortunately the Fritschen radiometer was more affected by rain drops on the domes than the Sauberer-Dirmhirn model at this very wet site. Also the results of the EFEDA study in Spain (Sene *et al*, 1992) required a correction by adding 4% of incoming solar radiation to these same instruments. Using the same days of data, the recovery ratio using the uncorrected Q*6 radiometer was 1.16 and with the correction 1.06. This uncertainty precluded it from being used as the primary net radiometer. Nevertheless, the Q*6 measurements suggest that the AWS net radiometer was not in error by a large amount.

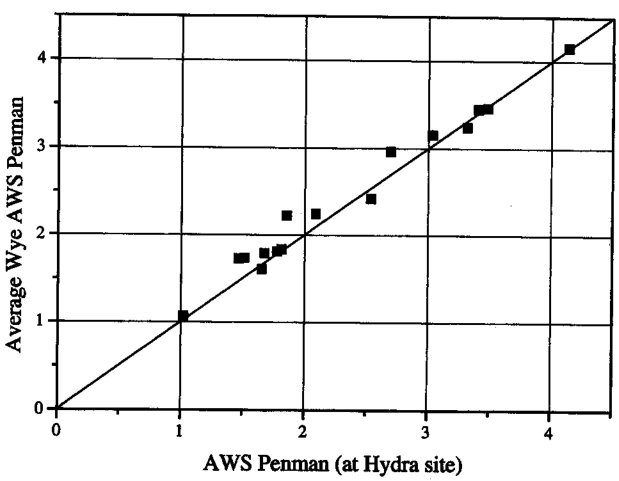


Fig. 7. *Penman Estimate compared to others in the Wye catchment.*

The E/PE ratio calculated from the rainfall-runoff data used the average of the Penman Estimate from the two Wye Automatic Weather Stations described at the beginning of the Results section. The data from these two stations have been quality controlled and corrected. The AWS at the Hydra site had been serviced and calibrated prior to being installed for these two months. A comparison between the mean daily Penman estimate from the two Wye stations with that from the AWS used in this study is shown in Fig. 7 and shows no significant difference.

## Conclusion

The study presented here has shown that Penman potential evaporation overestimates actual evaporation from grass in the Plynlimon catchment on dry days in summer. With this choice of data, there is a bias away from the days with intercepted rain, that therefore have a very low surface resistance. Thom and Oliver (1977) show that the Penman (1948) equation overestimates summer time evaporation for the same reason. In this study, the measured average E/PE of 0.83 with 0.09 S.D. for 16 mostly dry days is therefore consistent with the findings of the revised catchment measurements, where evaporation is calculated as the difference between rainfall and runoff and which suggest that for 1992 the E/PE was 0.91, using the two Wye AWS. On an annual basis, this difference in E/PE ratio is equivalent to only 48 mm of evaporation or less than 2% of the annual rainfall. Also the standard deviation of the catchment measurement of annual E/PE for 1978 to 1995 was 0.15.

Thom and Oliver (1977) have shown that the Penman formula contains an implicit empirical representation of the effects of the aerodynamic and plant physiological behaviour of the surface. This empiricism can be formulated explicitly in terms of aerodynamic and surface conductances of the Monteith (1965) version of the equation. Clearly, there is a need to quantify the behaviour of upland grassland in terms of these variables and to compare them with those derived from conditions where the Penman formula gives more accurate estimates. The data set presented here is not adequate for this task; a larger one is required. The Hydra has been stretched to the limit of its performance range in this situation and future studies would be better carried out using a 3-dimensional sonic anemometer where co-ordinate rotation can be used to establish the plane of the streamlines. The frequency of rainfall at the site is also a considerable disadvantage leading to only a small proportion of days yielding usable data.

## Acknowledgements

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## References

Hudson, J.A. and Gilman, K. 1993. Long-term variability in the water balances of the Plynlimon catchments. *J. Hydrol.*, **143**: 355–380.

Shuttleworth, W. J., Gash, J.H.C., Lloyd, C.R., McNeil, D.D., Moore, C.J. and Wallace, J.S. 1988. An integrated micrometeorological system for evaporation measurement. *Agric. For. Meteorol.*, **43**: 295–317.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. R. Soc. Lond. A*, **193**, 120–145.

Hudson J.A., Crane, S.B. and Blackie, J.R., 1997. The Plynlimon water balance 1969–1995: The impact of forest and moorland vegetation on vegetation and streamflow in upland catchments. *Hydrol. Earth Systems Sci.*, 1, 409–427.

Panofsky, H.A. and Dutton, J.A., 1984. *Atmospheric Turbulence.* Wiley, New York, 397pp.

Halldin, S. and Lindroth, A. Errors in net radiometry—Comparison and evaluation of 6 radiometer designs. *J. Atmos. Oceanic Tech.*, 9, No. 6: 762–783.

Sene, K.J., Oliver, H.R. and Cropley, F.D., 1992. Basic meteorological data intercomparisons between IH, Reading and CNRM groups in EFEDA, June 1991. Preliminary report to the EFEDA Secretariat.

Thom A. S. and Oliver H. R. 1977. On Penman's equation for estimating regional evaporation. *Quart. J. Roy. Meteorol. Soc.* 103, 345–357.

Monteith, J.L., 1965. Evaporation and environment. In: *State and Movement of Water in Living Organisms*, 19th Symposium of the Society for Experimental Biology. Cambridge University Press, Cambridge, pp. 205–234.