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The impact of site factors and climate variability on the calculation of potential evaporation at Moel Cynnedd, Plynlimon

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Abstract

The meteorological record from the manual Moel Cynnedd climate station at Plynlimon in the Welsh Uplands has been supplemented with solar radiation data, initially from the Institute of Hydrology's Dolydd Office, and later from an adjacent automatic weather station, in order to calculate Penman potential evapotranspiration for the entire 27 year data set, 1969–1995. The methods of data capture are consistent with Meteorological Office criteria throughout the entire record, establishing an unbiased and probably unique indicator of climatic variability and change for this type of environment. Values of Penman E_t calculated from these data provides an independent index of atmospheric demand for moisture as an adjunct to the hydrological studies being carried out in the Plynlimon and neighbouring catchments. Analysis of the long term data indicates considerable year-to year variability in the component variables, including some cyclical changes and possible long term trends in measured temperature. Annual variability in E_t is less than in the component variables, and there is an indication of a possible long term cycle, but no evidence of an overall trend in E_t during this particular study period. The results indicate that some of the observed variability can be explained by inevitable changes in exposure within this forest clearing site rather than changes in regional or global climatic patterns. A single meteorological station sited in a forest clearing at a relatively low altitude may underestimate potential evaporation across the catchment, as this will also include areas of exposed hillside and forest canopy.

Introduction

Since 1968, the Institute of Hydrology has maintained a U.K. Meteorological Office (MO) sponsored climate station at Moel Cynnedd (altitude 350 m) in the Plynlimon experimental catchments. The station was originally set up to provide climate data for a programme of hydrological and environmental research in the 8.7 km^2 upper Severn catchment, which is 68% covered by part of the Hafren Forest. The station is run to MO guidelines, and standard manual instrumentation is read at 0900 GMT every day. This is backed up by autographic temperature, humidity and rainfall recorders for quality control and infill. In spite of the addition of a network of automatic weather stations (AWS) in the mid-1970s, and the continuing technological advances that have been made in environmental sensors and data loggers, the manual climate station has been maintained in its original form. It provides one of the longest runs of consistent, quality-controlled data for this type of environment, and is unique in the Welsh uplands. Comparison of this dataset with the national network of MO sites provides an indicator of spatial and temporal climate variability during a period of alleged global change (Houghton *et al.*, 1990).

The primary research use of the meteorological data from Moel Cynnedd, however, has been to estimate the atmospheric demand for moisture, or potential evapotranspiration (E_t), over a vegetated surface using the Penman (1948; 1949) equation. This index represents an important adjunct to the water balance data being collected concurrently from the surrounding Severn and nearby Wye catchments (Kirby *et al.*, 1991; Hudson *et al.*, 1997c), and it has also been used as the best available index for the Llanbrynmair catchments some 22 km away (Hudson *et al.*, 1997c). The subsequent deployment of spatially distributed AWSs within the Plynlimon experimental catchments (Strangeways, 1972), and the use of automated data processing routines (Roberts, 1989), was intended to provide hourly meteorological data to supersede the calculation of E_t from Moel Cynnedd manual daily data. However, the automated approach does not fit the empirical framework or assumptions inherent in Penman's equation and is better suited to the Monteith, (1965) variation on this equation developed specifically for use with hourly data.

Creating extended datasets by combining AWS and manual estimates must be carried out with caution due to the differing methodologies employed in data collection and processing. Failure to ensure compatibility between data sets can produce steps in the E_t record due solely to the methodology and not to climate change (Hudson & Gilman, 1993). At Plynlimon, the AWS record does not become acceptably reliable until 1975/6 due to the experimental nature of the technology at the time. Revision and further quality control of the archived AWS datasets is still necessary to provide comparable consistency to the manual data. Hence, the manual E_t record from Moel Cynnedd represents the longest and most consistent index of atmospheric moisture demand available. Several papers in this issue attest to the importance of the E_t record (Hudson *et al.*, 1997c & 1997d; McNeil, 1997) to the interpretation of the hydrological, particularly evaporation, characteristics of upland catchments.

Recording the independent climatic variables which contribute to the determination of E_t, makes it possible to study long term cycles and trends in the climate of upland Wales that may have important implications for hydrology and ecology. Examination of how the manual and AWS E_t estimates compare within the same catchment, and how the various AWSs, subject to different environmental controls such as altitude and exposure, compare with each other, also helps to give a clearer picture of the spatial variation in evaporative demand on the catchment scale.

Impacts of Site Factors and Instrument Types on Calculation of E_t

The Penman estimation of E_t, as described in Blackie & Simpson (1993), can be represented by the following equation.

$$E_t \frac{\Delta}{\Delta+\gamma} R_n + \frac{\gamma}{\Delta+\gamma} EA \qquad (1)$$

where EA is a function of wind speed and specific humidity deficit, R_n is the net radiation, Δ is the slope of the saturated humidity/temperature curve at the dry bulb temperature and γ is the specific heat of air at constant pressure divided by the latent heat of vaporisation of water. The Penman estimation of E_t requires the following observations for calculation: a mean daily temperature derived as the mean of the daily maximum and minimum temperatures; wet bulb depression from 0900 hrs dry and wet bulb temperatures; daily wind run and net radiation.

The individual terms in Eqn. 1 are named after the dominant physical process each describes, i.e. the net radiation term is known as the 'Energy Budget' (EB), and the wind-humidity term as the 'aerodynamic' (AD) component. The energy budget term represents the energy made available for heating the atmosphere above the crop and for providing the latent heat of vaporisation, and is most conveniently and accurately measured using net radiometers. This is now standard practice with Institute of Hydrology AWSs; however, the Moel Cynnedd manual instrumentation predates commercially-available net radiometer sensors, and experience with the AWS net sensors also suggests that their reliability is suspect and it is difficult to ensure optimum sensor performance. For the sake of consistency over the complete 29-year Moel Cynnedd dataset, therefore, it was decided to rely on available solar records, and to calculate net radiation from solar radiation and air temperature data using a typical albedo for grass of 0.2 (Plinston & Hill, 1974; Roberts, 1989).

Moel Cynnedd has always conformed to MO standards for instrument type, position and method of measurement (Met. Office, 1969), with the exception of anemometer height and the method of measuring solar radiation. The standard MO anemometer height is 10 m, whereas wind is recorded at Moel Cynnedd records the standard agrometeorological height of 2 m for the calculation of Penman E_t. A correction factor to 10 m height is applied when supplying wind data to the MO.

SOLAR INSTRUMENTATION

The standard solar instrumentation used at most climate stations is the Campbell-Stokes (C-S) sunshine recorder, which allows estimation of short wave energy input on any given day as a function of sunshine hours and maximum possible radiation for that day. A sunshine hours recorder does not provide as sensitive a record of solar energy flux as a dedicated solarimeter, but is more reliable and data are readily available at most UK met. sites. The C-S recorder was run in parallel with a Kipp solarimeter between 1972–74 at Dolydd, the Institute of Hydrology's Plynlimon Office, some 5 km away from the Moel Cynnedd met. site (Fig. 1) because electric mains power was available there. The absence of direct solar radiation measurements at Moel Cynnedd was a problem until 1975 when an AWS with an integral Kipp solarimeter was installed within the same forest clearing (AWS Tanllwyth).

To provide a full record of solar (net) radiation the Moel Cynnedd record for the pre–1975 period has had to be inferred from the Dolydd records. Dolydd was a convenient site for instruments that required electrical power; this was before the advent of low power consumption instrumentation such as the Institute of Hydrology/ Didcot Instruments AWS. An AWS of this type was introduced to the Dolydd site in 1989. Ample data have been collected to check the differences in radiation climate between the two sites and to enable adjustment of the early (pre-1975) Dolydd solarimeter values to allow for different site characteristics (Fig. 2). The Dolydd site is at a lower altitude (308 m) than Moel Cynnedd, with a considerably drier climate, so some difference in radiation levels might be expected.

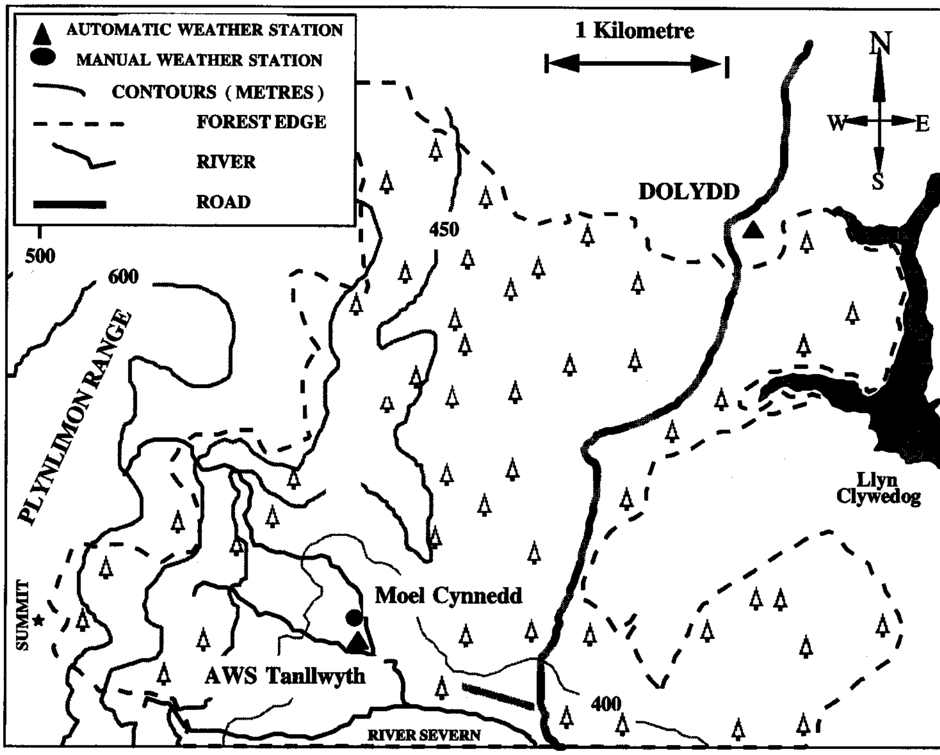

Fig. 1. *Locations of the Dolydd and Moel Cynnedd met sites and automatic weather stations in relation to the Hafren Forest on the south eastern slopes of Plynlimon.*

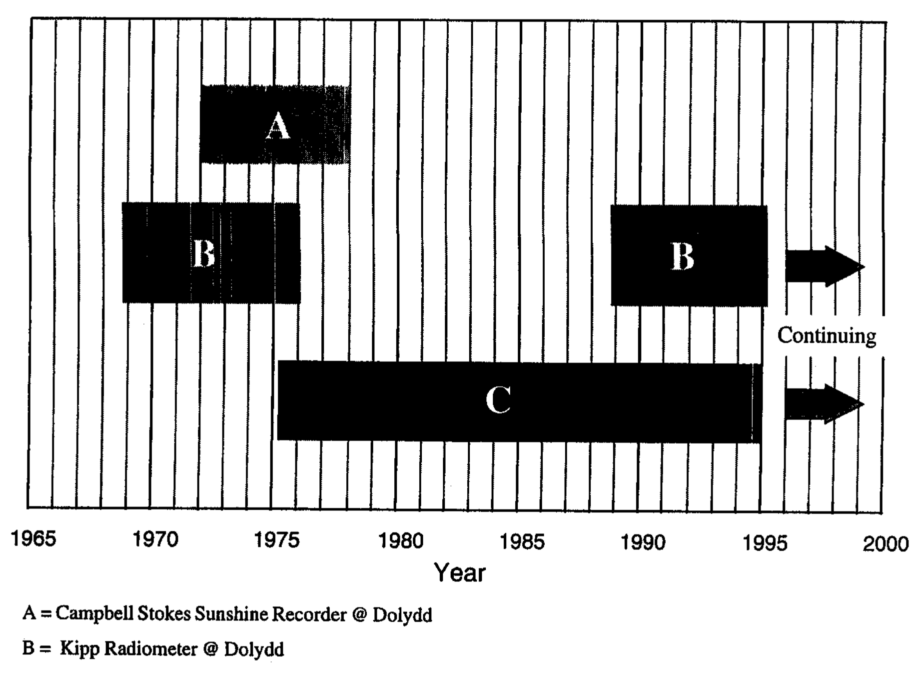

Fig. 2. *Periods of use of various solar radiation instrumentation at Dolydd and Moel Cynnedd.*

Table 1. Relationship between Kipp solarimeter daily solar radiation data (MJ m^{-2}) from the Dolydd and Tanllwyth automatic weather stations from 1989–95 using a linear regression

Depend.	Independ.	Coefficient	Intercept	Sample	r^2
Tanllwyth	Dolydd	0.98	–0.28	2132	0.97

SITE DETAILS

The forest clearing site at Moel Cynnedd has a regulation short grass cover maintained by regular mowing. It is more sheltered than Dolydd, although the degree of exposure has varied over the study period. In 1968, it was surrounded by c.20 year old trees of height c.6 m, which meant that the diameter of the clearing had to be maintained at 25 m at least, but in practice was considerably more than this. At intervals of two to three years, MO inspectors have checked the exposure horizon of the instruments and recommended an increase in the size of the clearing. Tree clearance, carried out by the Forestry Commission (now Forest Enterprise), has inevitably led to step changes in the microclimatic characteristics of the site, but it has proved difficult to reconstruct an exposure history for the site to quantify this. More recently, large-scale felling in the surrounding area, the inevitable consequence of forest economic maturity, has created significant changes in site exposure, and will continue to do so until the forest is fully re-established.

In addition to the full manual site at Moel Cynnedd and the AWS at Dolydd (1989 onwards), the Plynlimon catchments have four other AWS sites, two in each of the Severn and Wye catchments, one at a relatively high altitude and one at low altitude in each case.

Data Record

The manual daily weather data archive is subject to extensive quality control, both at the time of measurement, and also *en bloc* once the monthly data returns have been received by the MO; here, data are checked against expected ranges, for logical anomalies, and for unexpectedly large departures from other nearby MO stations. The calibration of the site instrumentation is also checked by the MO inspectors on their visits.

Independent checks on manual data by comparison with parallel measurements are seldom possible at climate stations due to the cost of duplicating instrumentation and because of confidence in the accuracy of the single set of simple instruments. Moel Cynnedd has an advantage over most met. sites in that the intensive catchment instrumentation present for the Plynlimon study allows cross-reference with 5 AWSs within comparatively small distances (~5 km) of each other. This does, however, introduce the statistical problem of comparing data sets with different sampling frequencies.

Of the E_t component variables, it is the solar record that has caused the majority of problems of data availability and instrumental continuity.

SOLAR RADIATION

From 1969 to 1974, the solar monitoring program at Dolydd relied on the Kipp Solarimeter, backed-up between 1972 and 1974 by the Campbell-Stokes (C-S) sunshine recorder. From 1975 onwards the preferred source of solar radiation data was a Kipp solarimeter atop AWS Tanllwyth located adjacent to Moel Cynnedd (Fig. 2), although the C-S sunshine recorder was still operational from 1975–1978. Comparison of data collected when AWSs were run concurrently at both Dolydd and Moel Cynnedd (1989–95) produced the relationship presented in Table 1.

Comparing the mean daily values of Moel Cynnedd (Tanllwyth) and Dolydd radiation indicates that a potential overestimation error of 6% is introduced by simply transferring the Dolydd values, which is enough to justify applying an adjustment to take into account site differences. Further analysis (Fig. 3) indicates that the deviation is not constant, and tends to a maximum in the mid-range of solar radiation values. This is believed to be because there is a higher probability of the radiation levels at the two sites showing a difference on partially cloudy days, than there is on those days that are either completely sunny or cloudy.

A better relationship for predicting the daily solar radiation (MJ m^{-2}) at Moel Cynnedd (R_{TAN}) from Dolydd data (R_{DOL}) is achieved by using Eqn 2. Constraining to $R_{TAN} = R_{DOL}$ at the minimum and maximum extremes of the observed radiation ranges and assuming a probability (Gaussian) distribution of the deviation from parity between these limits, gives:

$$T_{TAN} = R_{DOL} + y_0 + Ae^{-(x-x_c)^2/2w^2} \quad (2)$$

where the parameters have been optimised using the Gaussian Amplitude function from Microcal Origin® as:

$y_0 = -0.01 \quad A = 0.7546 \quad x_c = 14.796 \quad w = 9.327$
$x = R_{DOL}$

This analysis covers the years 1989–95, but is assumed also to hold for the early years (1969–74) for which data are not available. By comparing the total yearly solar radiation received at both sites to that of the theoretical maximum

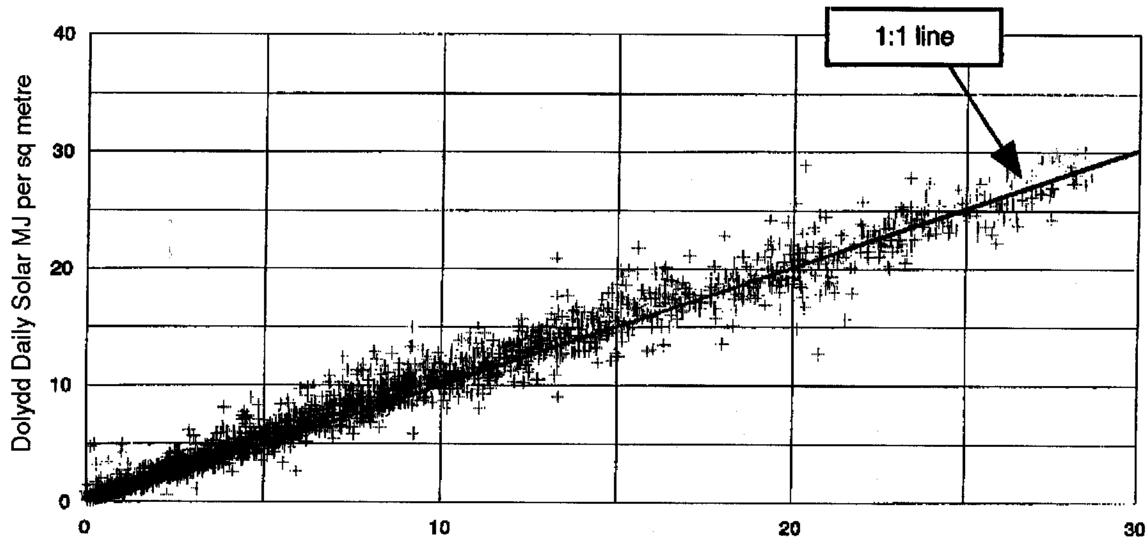

Fig. 3. *The relationship between daily solar radiation values (MJ m*$^{-2}$*) from the Dolydd and Tanllwyth (Moel Cynnedd) automatic weather stations, 1989–1995.*

for cloudless skies predicted via the Angstrom equation (Glover & McCulloch, 1958) and calculating the ratio between them, it is possible to examine if the sites are detecting approximately the same total solar flux over the study period even when data are not complete. Defining the months April–September as the 'solar year' minimises the confounding effects of topography reducing solar radiation at low solar altitudes.

Figure 4 displays the 1969–74 solar data (as a ratio to the theoretical incident clear-sky solar radiation) from the Dolydd Kipp in comparison with data from Dolydd and AWS Tanllwyth recorded during later years. The figure

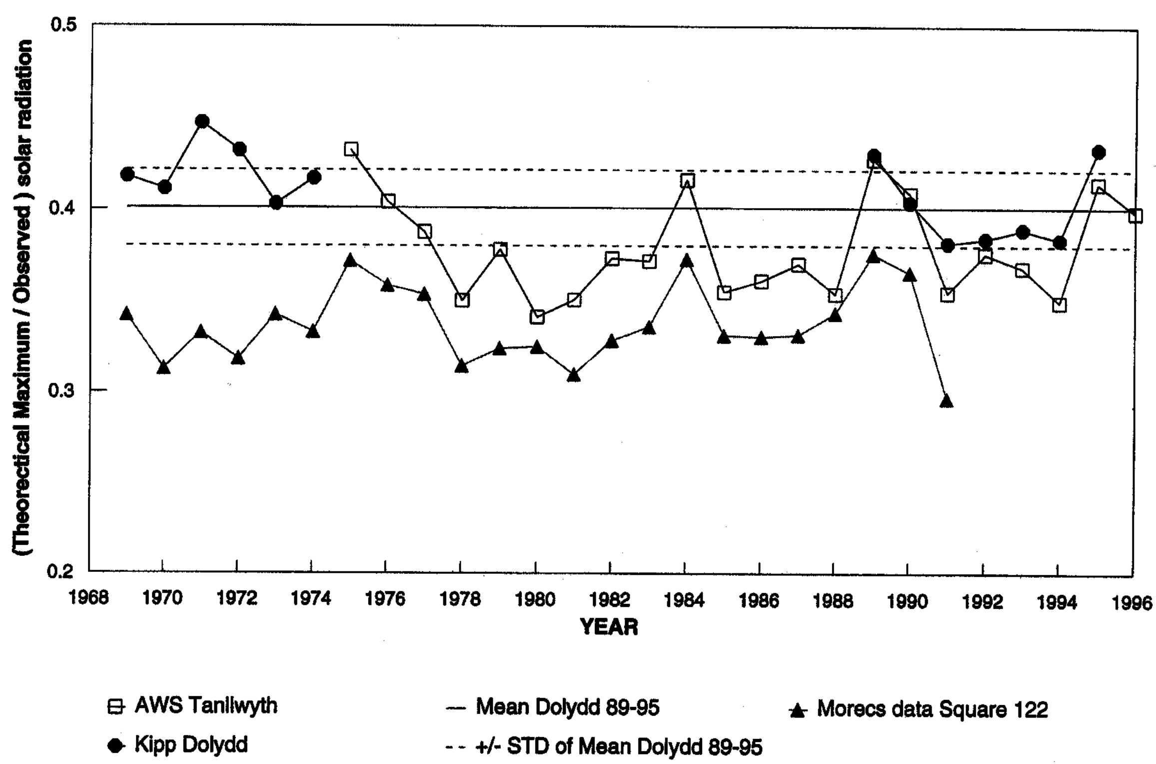

Fig. 4. *Time series of the annual ratio of solar radiation input (April–September) to the theoretical maximum from the Angstrom equation, for the solarimeters at Dolydd and Tanllwyth and regional MORECS square.*

shows firstly that the early Dolydd ratio is high with respect to the subsequent AWS Tanllwyth data, which is reasonable considering the intersite evidence presented above. Secondly, it shows that the early Dolydd values are consistently higher than for the same site after 1989, although 4 out of 6 data points do lie within one standard deviation of the post-1989 mean. Thirdly, early Dolydd data do not follow the trend evident prior to 1975 in the MORECS solar record for the surrounding 40 km × 40 km grid square. MORECS is used as a comparison because it represents the only available local solar dataset with a record at least as long as that of AWS Tanllwyth, but it should also be noted that MORECS radiation is derived from sunshine hours and as demonstrated later can give values consistently lower than data from the radiometers. Even if this is taken into account, it is still noticeable that the differences in the early years, 1969–75, between MORECS and the adjusted Dolydd data (see Fig. 12 for Dolydd values adjusted to represent Moel Cynnedd) are greater than the post–1975 differences. This leaves a small doubt as to whether the Dolydd adjustment derived for 1992–1995 is applicable to the pre-1975 Dolydd record; however, the discrepancy could just as easily be due to changes over time in the way MORECS evaporation has been calculated, for instance, in the number of sites used or their spread within the grid square.

It may not be possible to prove conclusively from the available data whether the record describes a higher solar regime at Dolydd, whether there is an instrumental bias in the Dolydd data, or whether a data bias has been introduced in years when large amounts of data are missing from the ratio calculation. However, there being no better option, adjusted solar data from the Dolydd Kipp have been used at Moel Cynnedd for the initial years (1969–74). At least this approach minimises systematic errors introduced by using more than one instrument design, and also avoids the operational limitations inherent in the C-S recorder which is insensitive to the level of solar radiation when below or above the ignition threshold intensity; it also has limited accuracy in the time base, i.e. the solar input is recorded as being either present or not present, and is determined to only 1/10th hour (6 mins) accuracy (Fig. 5 and Table 2).

The solar radiation data record for the period 1975–95 has not been free from problems either, with system failure and data loss more common in the early years. Data infilling for the Moel Cynnedd radiometer has been necessary at various times, but has been most problematical for the first 113 days of 1975, when the Dolydd C-S was the only recorder operational. The above-mentioned problems with interpreting sunshine data and converting to solar radiation, dictated the use of a different technique for infilling the period before the AWS Kipp came on-line on Day 114 that has also proved useful for infilling the rest of the radiation record when alternative radiometers were not available.

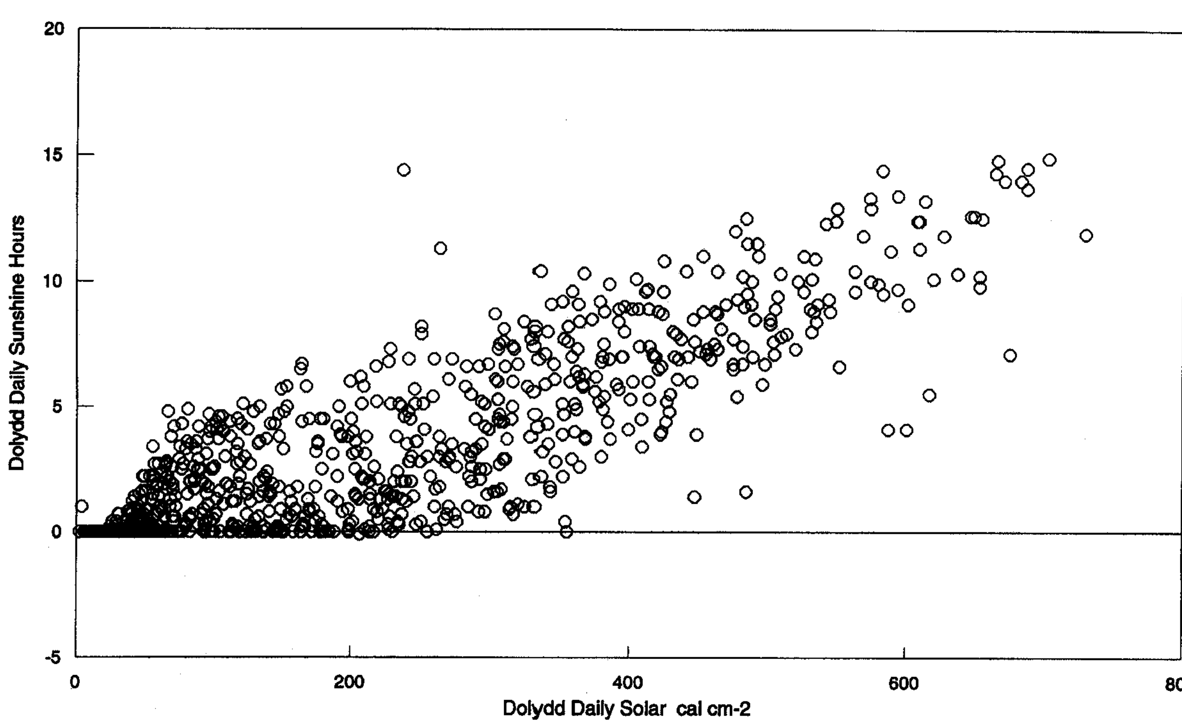

Fig. 5. *The relationship between daily solar radiation and sunshine hours at Dolydd, 1972–1974.*

Table 2. Relationship to estimate daily solar radiation (cals cm^{-2}) at Dolydd from sunshine hours (1972–74)

Depend.	Independ.	Coefficient	Intercept	Sample	r^2
Solar Radiation	Sunshine Hours	40.7 ± 0.9	79 ± 91	859	0.71

Solar Infill

Periods of missing data requiring infill ranged from solitary days to several months. The various infilling methods used depend on the system of backup that was operational at the time. From 1969–71 only the Kipp solarimeter at Dolydd was operational. Missing data for this period have been infilled by applying a reduction factor to the curve of maximum theoretical radiation derived from the Angstrom equation to achieve a 'best fit' scenario with the available data. (Fig. 6). The magnitude of the reduction factor has to be considered as 'year specific' because the Angstrom equation assumes no change from year-to-year in either the exposure horizon or the frequency of cloud cover, an unrealistic premise in an upland forest clearing (Table 3). It is most important to simulate the summer radiation, as this contributes the major portion of annual E_t, so the reduction factor was calculated from April–September totals (see later: Table 4). This method cannot simulate the random nature of daily solar input, but nevertheless produces sensible values which lie within the expected operational range.

From 1972 until early 1975 the Kipp and C-S sunshine recorders were run in parallel at Dolydd. This allows two possible means of infilling missing radiation for this period, either using the reduction factor technique or by deriving a relationship between the Kipp Solarimeter and the C-S recorder. The numerical correlation between Solar input (Kipp) and sunshine hours (Fig. 5 & Table 2) is not as strong as might be expected even though each instrument is measuring a form of solar input. There are many days where the total measured solar radiation is significant but below the ignition threshold of the C-S card, an effect that is particularly pronounced at low solar angles. Although sunshine hours are 'real data', providing a record of actual conditions, it was decided that this infilling method tended to underestimate solar radiation. The solar reduction method was therefore used where possible.

From mid-1975 onwards, it has been possible to infill solar data when the Tanllwyth AWS Kipp has malfunctioned by using relationships derived with the other AWSs in the catchments.

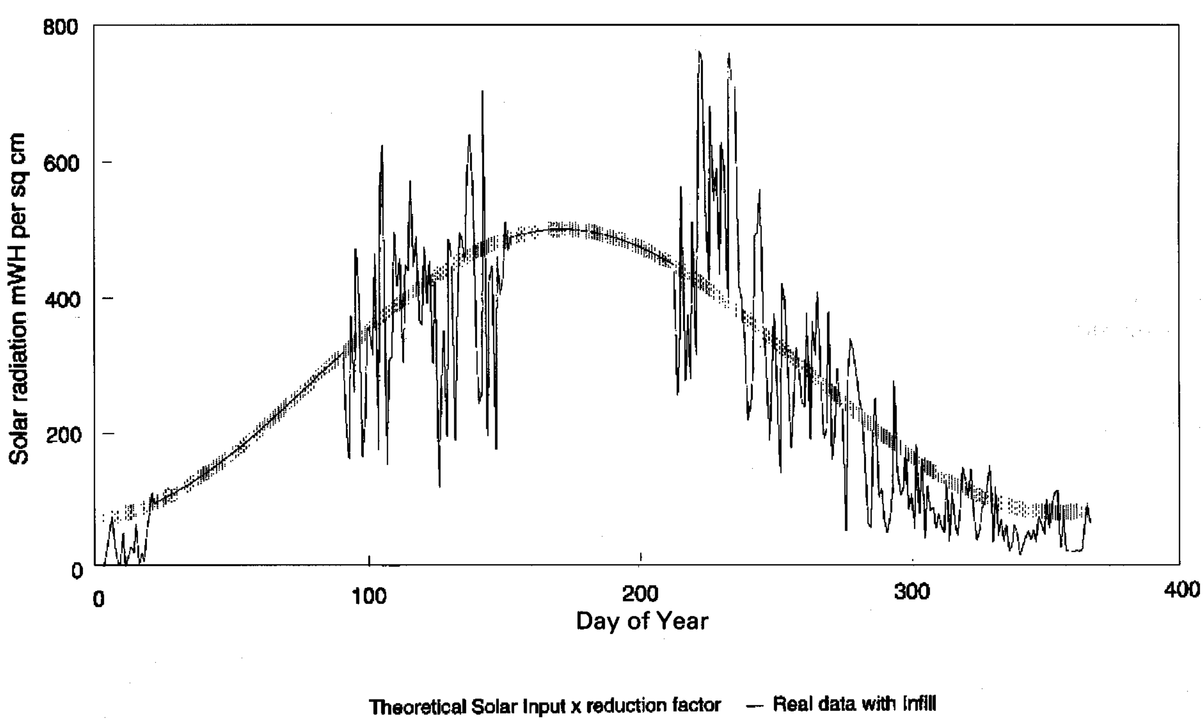

Fig. 6. *An example of infilling missing solar radiation data, using the solar reduction factor method.*

Table 3. Long term least squares analysis of climatic variable gradients from Moel Cynnedd.

Variation in Annual Means	Pre-Felling MWS (68–86) AWS (76–86)	Post-Felling (87–95)	Total Period MWS (68–95) AWS (76–95)
WIND SPEED (m s^{-1} yr^{-1})			
MWS	–0.012 +/– 0.004	0.018 +/– 0.008	–0.006 +/– 0.002
AWS Tanllwyth	–0.013 +/– 0.010	*nst*	–0.021 +/– 0.004
MWS TEMPERATURES (°C yr^{-1})			
0900 Dry	*nst*	*nst*	0.014 +/– 0.011
0900 Wet	*nst*	*nst*	0.019 +/– 0.010
0900 Wet Depression	*nst*	0.026 +/– 0.015	–0.005 +/– 0.003
0900 Wet Depression (3 yr mean)	–0.006 +/– 0.004	0.026 +/– 0.008	–0.006 +/– 0.002
Maximums	*nst*	*nst*	0.021 +/– 0.014
Max. (3 yr mean)	*nst*	*nst*	0.015 +/– 0.001
Minimums	*nst*	*nst*	0.033 +/– 0.009
Min (3 yr mean)	0.009 +/– 0.008	*nst*	0.032 +/– 0.006
Mean	*nst*	*nst*	0.027 +/– 0.010
3 yr mean	*nst*	*nst*	0.023 +/– 0.008
SPECIFIC HUMIDITY DEFICIT (g kg^{-1} yr^{-1})			
MWS @ 0900 hrs	*nst*	0.016 +/– 0.009	*nst*
MWS @ 0900 hrs (3-yr)	–0.004 +/– 0.003	0.008 +/– 0.007	–0.003 +/– 0.001
SOLAR RADIATION (W m^{-2} yr^{-1})			
AWS TAN *	–0.81 +/– 0.27	*nst*	–0.36 +/– 0.16

* starting year 1969 and 1969–74 from adjusted Dolydd solar data *nst* - no significant trend

Long Term Variability in Climate

The climate variables needed to calculate E_t can be analyzed independently to assess the sensitivity of the E_t estimate to long term trends in its component variables. The existence of trends caused by climate or otherwise is indicated by the analysis in Table 3.

Wind Speed

The long term records of mean annual windspeed for both the Moel Cynnedd manual weather station (MWS) and AWS Tanllwyth, which are located approximately 75 m apart within the forest clearing, are shown in Fig. 7. The relative shelter of the forest clearing is indicated by comparison of either sensor with AWS Cefn Brwyn, which is sited at a similar altitude of 359 m to Moel Cynnedd, but in an exposed position in the Wye catchment. Wind speed at Cefn Brwyn is on average c. 2.5 times as fast as AWS Tanllwyth and c. 3.5 times as fast as Moel Cynnedd. It is clear from Fig. 7 that there is also a significant difference in measured wind speed between the two forest clearing stations, and in the data trends displayed. MWS data indicate a decline in wind speed from 1968–1986, followed by a period from 1986–1995 which shows the opposite trend (Table 3). AWS Tanllwyth shows a similar decrease to the MWS from 1976 to the mid-1980s, but after 1987 there is no significant trend.

Dry and Wet Bulb Temperatures, Wet Bulb Depression and Humidity

Wet bulb depression, the temperature difference between simultaneously observed wet and dry bulb thermometers, used to calculate atmospheric humidity, is measured once daily at 0900 hrs. Figure 8 shows the long term mean annual values for dry bulb, wet bulb and depression, with the 3-year running means shown in Fig. 9 to indicate more clearly the nature of long term variability in the data. Overall, AWS Tanllwyth agrees well with the MWS record for dry and wet bulb measurements, with the exception of 1977 and 1984 which have substantial amounts of missing data and have therefore been omitted

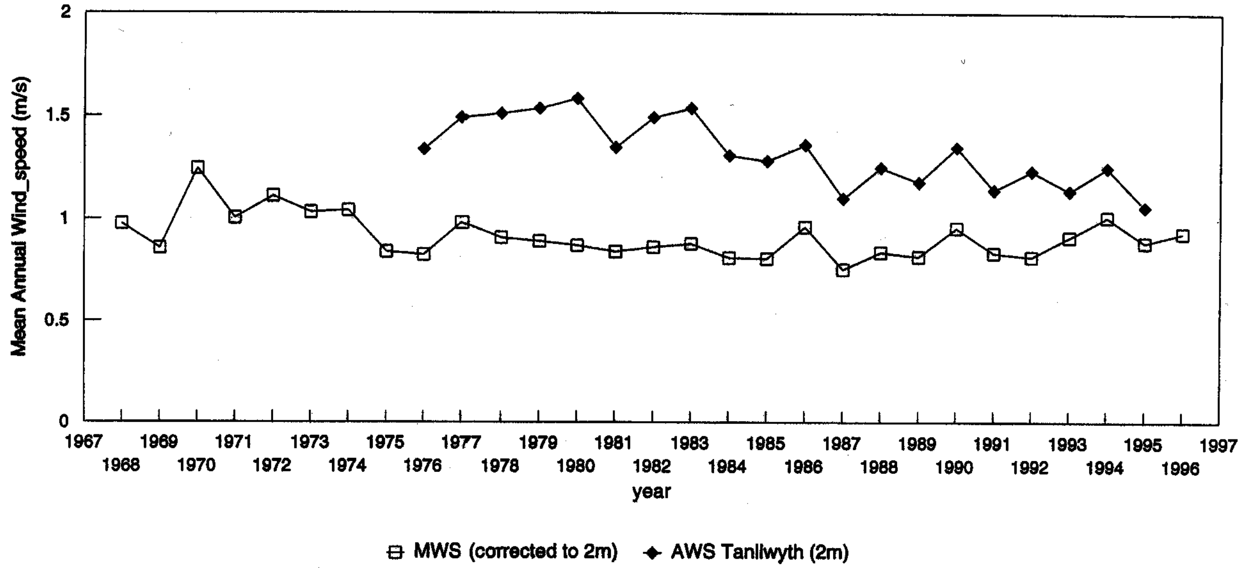

Fig. 7. *A comparison of the annual time series of wind speed for the manual and automatic weather stations at Moel Cynnedd (Tanllwyth).*

from the analyses. Over the data record the dry and wet bulb temperatures both show slight increases that are nevertheless well within the data range, but it is noteworthy that this range itself increases markedly after 1986. The long term trend in wet bulb depression in contrast reveals a distinct minimum centred around 1987.

Atmospheric humidity makes an important contribution to the calculation of the aerodynamic component of E_t, in the form of the specific humidity deficit (SHD), which is a direct measure of how much water vapour the atmosphere can absorb until saturation; the time series of SHD is shown in Fig. 10. As with wet bulb depression, the evidence for change in SHD suggests a decline to 1987 and an increase thereafter (Table 3). The trends are not easy to distinguish, because interspersed within the data are years of particularly high SHDs associated with drought

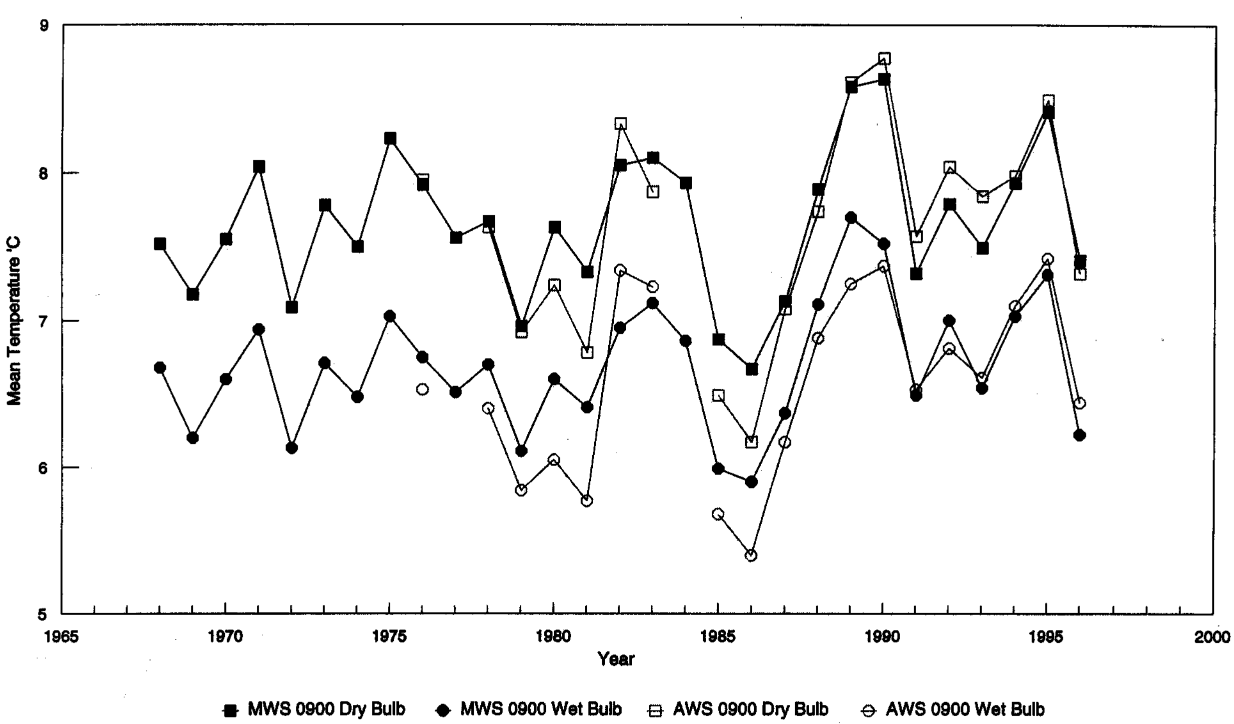

Fig. 8. *Time series of annual mean dry and wet bulb temperatures (0900 hrs) at Moel Cynnedd and AWS Tanllwyth.*

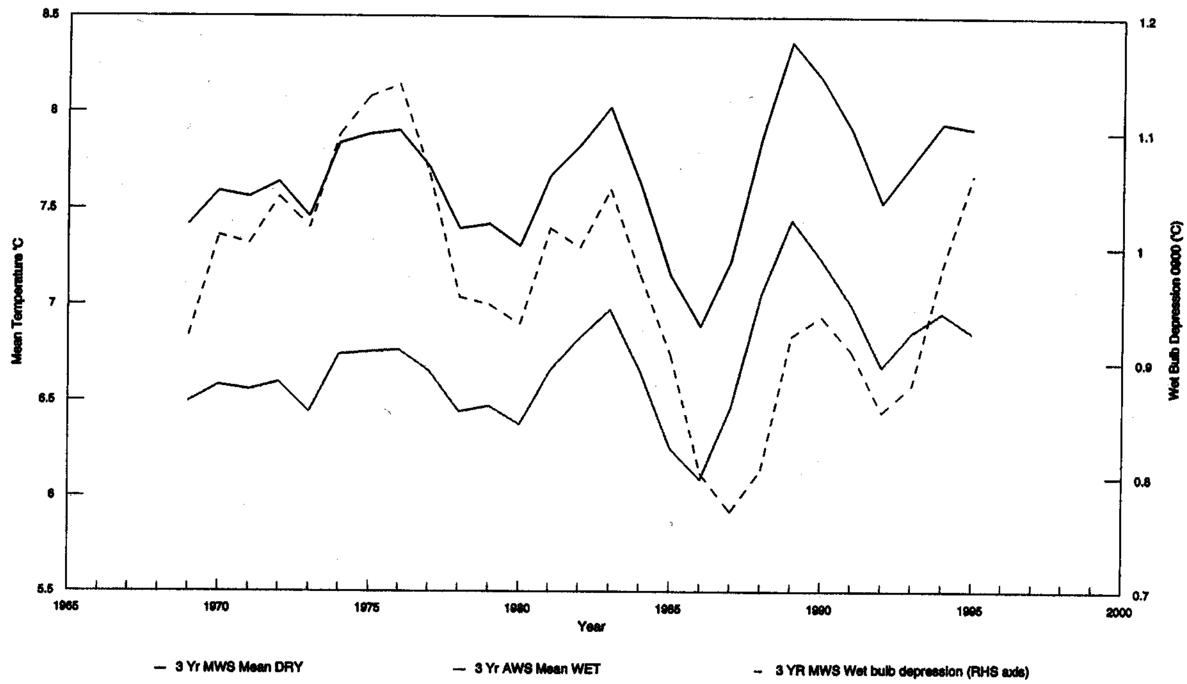

Fig. 9. *Time series of smoothed annual dry and wet bulb temperatures (0900 hrs) together with wet bulb depression for the Moel Cynnedd.*

years (e.g. 1975, 1976 & 1990) which produce pseudo-cyclic variations.

Comparison of MWS and AWS SHD datasets (Fig. 10) show absolute differences which could either be the result of the sampling method or the effect of microclimatic differences across the forest clearing. For the AWS, 0900 hrs SHD values are representative of humidity conditions for the whole day (in line with Penman's assumptions). For the MWS, however, the 0900 hrs spot SHD value is consistently lower (more humid) than the comparable AWS value. On average the MWS appears to be behaving more like the AWS does between 0700 hrs to 0800 hrs. This suggests that the proximity of the forest to the MWS is influencing measurement of this variable by introducing a

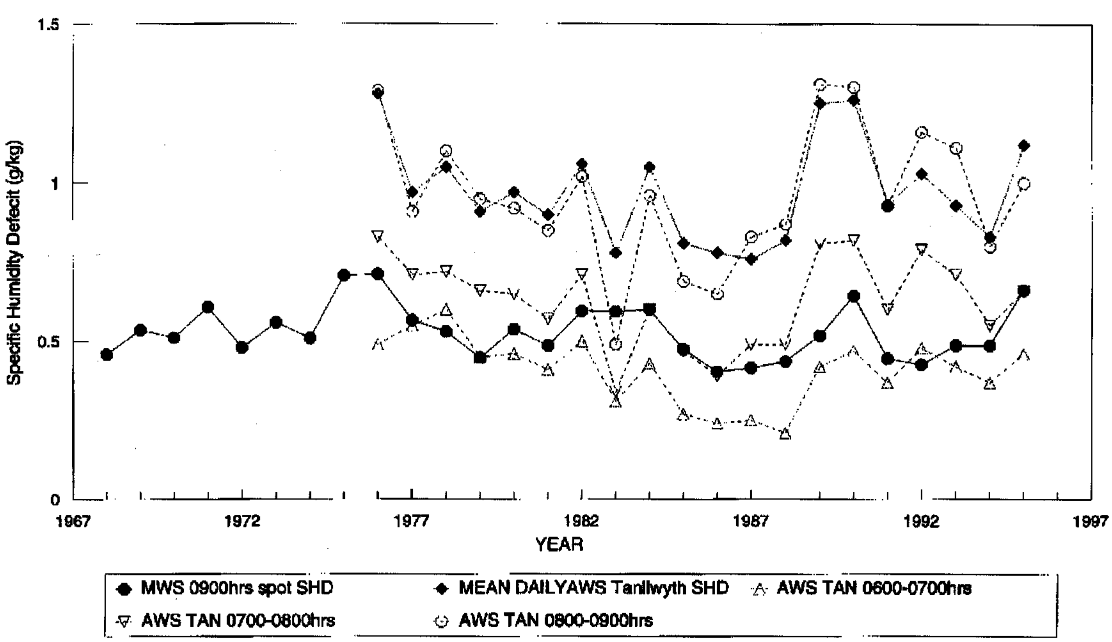

Fig. 10. *Time series of annual mean SHD (0900 hrs) at Moel Cynnedd, in comparison with mean hourly and daily SHD from the AWS Tanllwyth.*

lag effect, i.e. the nocturnal boundary conditions have not fully broken down by 0900 hrs at the MWS location.

Maximum, Minimum and Mean Daily Temperatures

The Penman equation requires an estimate of the daily mean air temperature, which is then associated with the 0900 hrs wet bulb depression in order to calculate a daily humidity value. With manual readings the mean daily temperature is taken as the mean of the daily maximum and minimum temperatures, while for the AWS the daily mean is a mean value of sub-hourly samples (Fig. 11).

Excluding AWS Tanllwyth data for 1977 and 1984 which contain missing values, the manual and automatic mean temperature datasets are in good agreement with respect to annual variability. The mean for the AWS is consistently lower than the MWS by approximately 1°C. It has not been determined whether this difference is due to the site locations or the method of determining the mean. All MWS variables displayed in Fig. 11 display slight positive gradients over the years 1968–1995 (table 3); the positive gradient of the minimum temperature shows the most significant trend.

Solar Radiation

This represents the most important control on variability in E_t. Using the various means of infilling described, a complete record of solar input has been generated for use with both Tanllwyth AWS and Moel Cynnedd manual data (Fig. 12). Trend analysis of the full 1969–95 dataset shows a very small decrease in mean hourly solar radiation, caused largely by the aforementioned high solar values during the initial years of the record, which are subject to substantial infill and manipulation. The long term decrease identified may be spurious.

As a means of checking the post–1975 years, AWS data from Cefn Brwyn is also shown in Fig. 12. There is good agreement for most of the record, but with clear exceptions during the first four years and 1983, although these discrepancies can be explained by missing data from Cefn Brwyn.

EVIDENCE FOR CLIMATIC CHANGE

Excluding solar radiation, which may have an artificial bias and is thus difficult to assess, all the component variables of E_t show evidence of varying degrees and directions of change over the study period which can essentially be split into two distinct categories. One form of change is a gradual trend throughout the entire dataset, whereas the other form shows a 'turning point' in behaviour around 1985–1987. It is probably no coincidence that the years 1985–1987 also mark the start of the clear-felling regime in the Severn catchment (Roberts & Crane, 1997), which has possibly affected atmospheric circulation in the Severn and the microclimate of the forest clearing in which the met. site is located.

The question is therefore: do the observed trends reflect a change in local conditions experienced at Moel Cynnedd or are they representative of a greater global change? Least squares trend analyses carried out on all the measured variables, both pre- and post-clearfelling, are presented in Table 3.

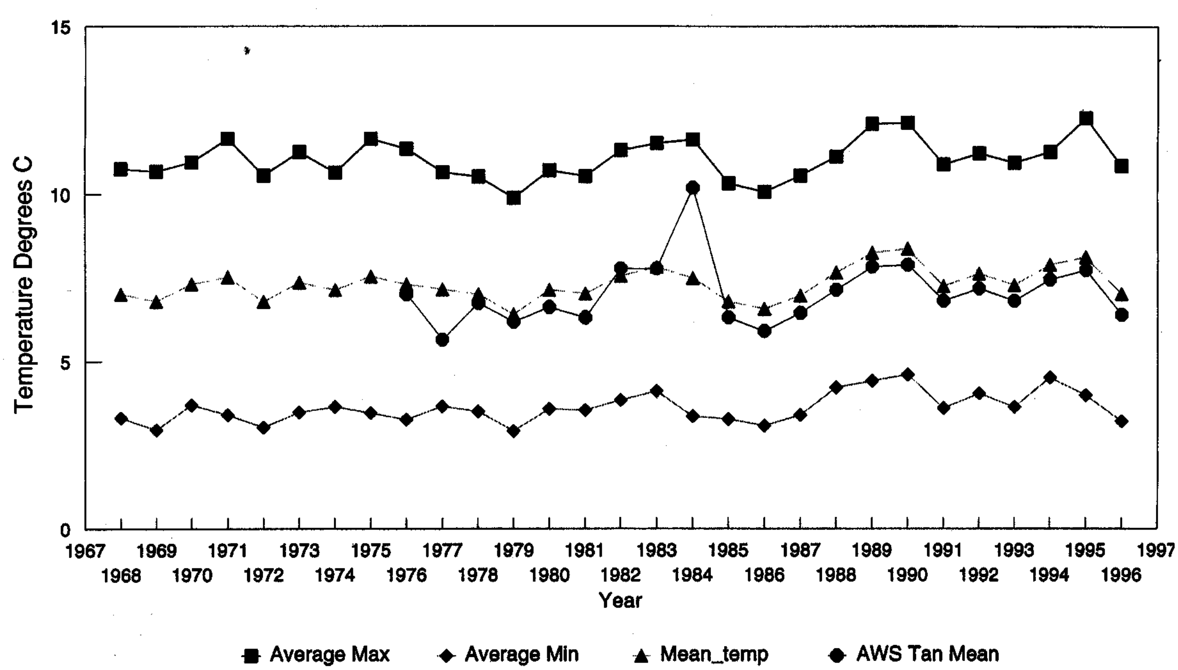

Fig. 11. *Time series of annual mean maximum, mean and minimum daily temperatures at Moel Cynnedd, with the mean daily temperature from Tanllwyth AWS for comparison.*

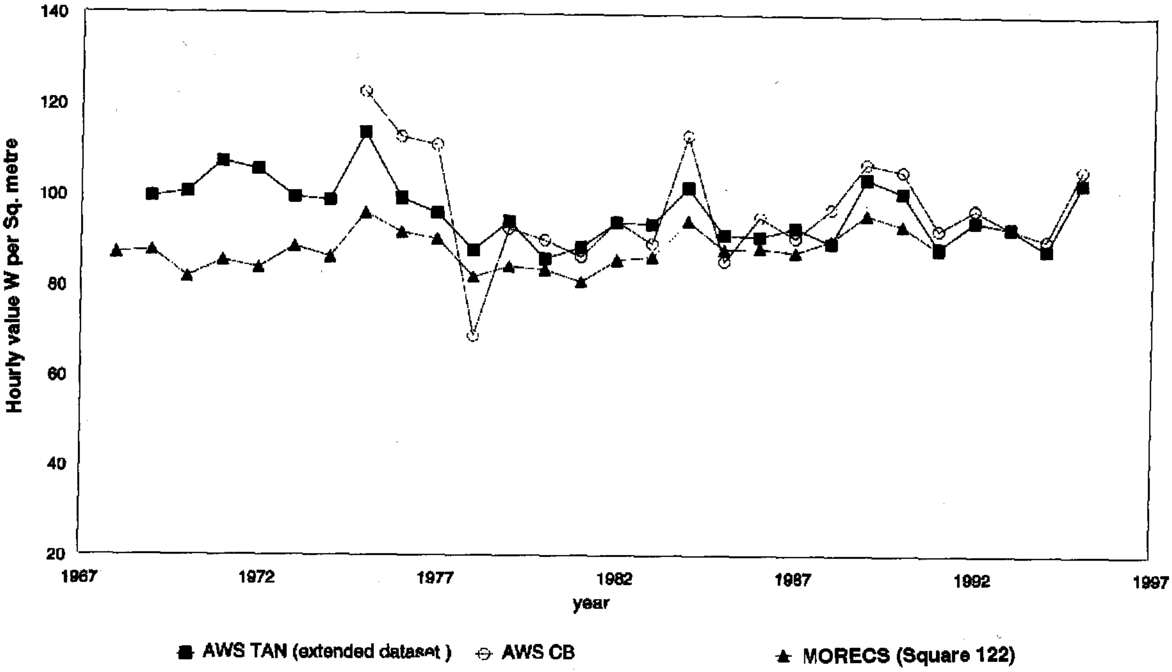

Fig. 12. *A comparison of the annual mean solar radiation inputs (Wm^{-2}) at Moel Cynnedd (comprising adjusted data from Dolydd 1969–74 with AWS Tanllwyth 1975–95) and Cefn Brwyn AWS.*

Solar radiation is the most important variable accounting for absolute levels of evaporation, but during the study, even allowing for problems with the solarimeters in the early years, variations have been small relative to the absolute magnitude of solar input. Site factors would be important if the forest was ever allowed to overshadow the solar radiometer but, as this has never happened, the variation in solar input must be climatic in origin.

The effect of a maturing forest canopy would be to gradually increase shelter within the clearing and hence progressively reduce windspeed. There is good evidence in the wind data to confirm this. However, the situation is complicated at Moel Cynnedd by periodic decisions, under MO guidance, to increase the clearing size to compensate for the increase in the height of the surrounding trees. In recent times (1994 onwards), clear felling of the trees in the area immediately to the west of Moel Cynnedd has dramatically increased exposure of the met. site. Although no step functions can be seen in the data that can definitely be attributed to local forestry activity, there are indications that the aerodynamic exposures of both sets of instruments have converged since the mid-1980s. This would be consistent with establishment of uniform exposure to wind over the whole clearing. With this local change, and the potential for future variation in forest cover, it seems unlikely that conclusive proof can be had from the current MWS dataset of climatic change in the Plynlimon area, until such changes become large compared to the effect of local factors.

In addition to the effect on measured windspeed of the variable shelter afforded by the forest, the surrounding forest also provides a fetch of freely transpiring and intercepting canopy, wetted by precipitation on approximately 240 rain days per year (Newson, 1976). Humidity may therefore reduce significantly after substantial local clear-felling, a feature that can be seen in SHD trends. Decreasing SHDs accompany the growing forest until the mid 1980's, but the trend is reversed with the advent of local clear felling.

The observed tendency of all the temperature measurements is more redolent of expected climate change, i.e. a progressive increase in absolute value rather than a 'turning point'. Hence, ascertaining if local changes, as opposed to global influences, are responsible for the observed trends assumes great importance. In damping the equilibrium to external influences, increased insulation of the met. site from the regional airflow could either increase or decrease the local diurnal range in temperatures. Whichever direction the effect takes, a reversal might be expected after significant felling.

The overall range of air temperature data values is such that only the 3-yr mean minimum shows a weak positive trend prior to 1986. There appear to be no significant subtrends within the data to suggest that local forestry work has had the major effect it had with the wind and humidity data. Regressions over the whole study period reveal only that temperatures are, on average, higher at the end of the study than at the beginning, with the minimum temperature showing the most significant change over the 27 year period. This may be because the minimum temperature is more a reflection of sustained daily phenomena at the MWS site, such as the overnight develop-

Table 4. **Estimates of annual E_t from Moel Cynnedd and its breakdown into energy budget and aerodynamic terms. The extent of missing solar radiation data and infill factors for the years 1969–75 are also shown; the latter is used in the solar reduction infilling procedure.**

Year	Total E_t (mm)*	Energy Budget Term (mm)	Aerodynamic Term (mm)	Missing data (days)	Infill ratio
1969	400	290	90	13	0.418
1970	405	290	102	66	0.411
1971	418	291	107	100	0.445
1972	393	280	99	132	0.432
1973	398	279	105	35	0.403
1974	393	287	100	42	0.416
1975	427	290	108	141	0.432
1976	438	317	106		
1977	400	289	101		
1978	380	279	91		
1979	372	281	78		
1980	373	266	95		
1981	367	272	85		
1982	399	289	101		
1983	395	292	88		
1984	425	318	97		
1985	366	266	83		
1986	354	271	74		
1987	366	284	67		
1988	357	273	72		
1989	431	344	78		
1990	425	314	101		
1991	367	275	77		
1992	381	294	72		
1993	382	283	89		
1994	371	274	86		
1995	435	323	101		
Mean 69–95	393	289	91		
% of E_t	—	74	23		
σ	±25	—	—		

* One anomaly in the calculation of the Energy Budget (EB) and Aerodynamic (AD) terms is that negative values occur which are set to zero in the daily summation to E_t but are left as-read in the individual components. Therefore: $EB+AD \approx E_t$.

ment of a stable boundary layer, than are the other climate variables. The degree of change in the minimum temperature (~0.3°C per decade) is consistent with claims made in recent global change studies (Houghton *et al.*, 1990).

The E_t Record

Calculation of Penman E_t using the component variables described gives results as illustrated in Fig. 13 and Table 4. E_t is calculated as the daily summation of the 'energy budget' and 'aerodynamic' terms. These terms represent the two physical controls on the movement of water molecules in the moisture surface during evaporation. The 'energy budget' term is the effect of direct energy input from an external source (solar) providing the latent heat of vaporisation. The 'aerodynamic' term is the freedom of molecules to leave the surface under the influence of humidity gradients and mass transfer of air in the ambient environmental conditions. The two terms are not entirely independent of each other, there being feedback for instance between radiation input, surface temperature and therefore air temperature. For numerical reasons arising from the separation of the two terms whilst using the Penman calculation (see footnote in Table 4) EB and AD terms often do not add up exactly to E_t. However, consideration of them as independent terms may show more indication of change than the overall E_t value, and may also help to explain any changes in terms of site factors.

The main control on E_t at a sheltered site such as Moel Cynnedd is from the EB term, which is dominated by solar input, and accounts for 74% of E_t. There is no obvious trend in the EB term, but there are sporadic years of especially high solar contribution. The most interesting feature of Fig. 13 is the trend displayed by the AD term. Having shown consistent behaviour until the early 1980's, it then declines to a minimum value in 1987 which is followed by a progressive recovery to levels close to those at the start of the record. Such a trend can be explained entirely by changes in local site exposure and its effect on the component variables. Lower wind speeds and lower temperature depressions are the logical result of increasing shelter from the maturing forest, while after 1985 the situation changes with the advent of clearfelling. The prevailing south westerly air stream incident on Moel Cynnedd will have had to traverse increasingly longer fetches of clear-felled land, which will have had the effect of decreasing the humidity (increasing SHD) at the site due to the observed crash in evaporation from the clear felled area upwind (Roberts & Crane, 1997; Hudson *et al.*, 1997b) compared to a mature forest.

It is not clear whether the changes noted in the AD term are primarily due to the changes in wind speed or in humidity. A sensitivity analysis of the AD term, using the values of mean annual wind speed and temperature depression as observed (Figs 7 & 9), and assuming an arbitrary variation of ±25% in each, results in the AD term changing by ±11% due to depression and by ±8% on account of the wind speed change. Thus, the AD term appears to be more sensitive to humidity than wind speed, and this is confirmed to some extent by the closely-matched shapes of the AD term and humidity curves.

Inter-Site AWS Comparison

Examination of the long term variability of upland climate was only a minor reason for setting up the Moel Cynnedd manual met. site, and subsequently the Tanllwyth AWS. Their main purpose was to provide indices of atmospheric moisture demand that were comparable with water balance estimates of evaporation from the whole of the Severn and Wye catchments. From a geographical perspective Moel Cynnedd is clearly not representative of either the Severn or the Wye, especially not the latter, but it can be argued that no one site could ever be regarded as 'typical'. An upland catchment in a cool temperate maritime climate with a considerable altitude range and rough topography is subject to steep temperature and humidity gradients as well as unusual, persistent phenomena such as cap clouds on the mountain tops. Determining a representative value of catchment E_t from just one low altitude forest clearing site is therefore not feasible.

Catchment scale variation in E_t can be observed when considering Tanllwyth (altitude 350 m) in relation to three other operational AWSs within the catchments: at Carreg

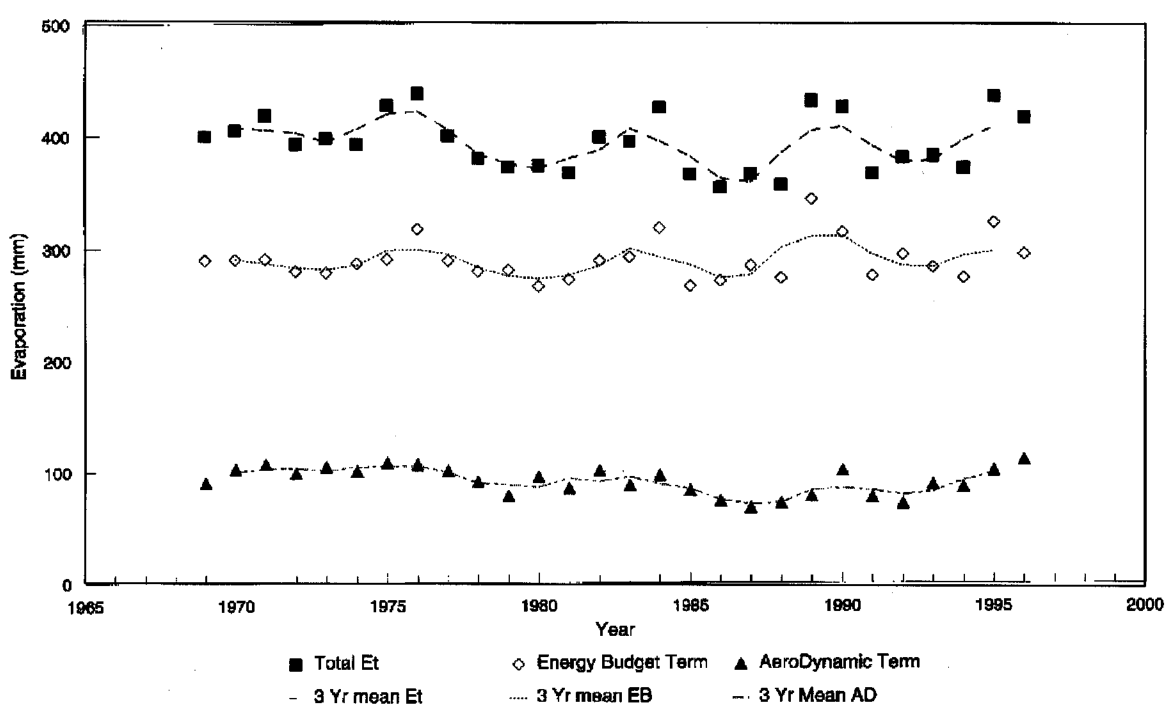

Fig. 13. *A time series, 1969–1995, of the breakdown of the annual E_t estimate at Moel Cynnedd into the energy budget and aerodynamic components.*

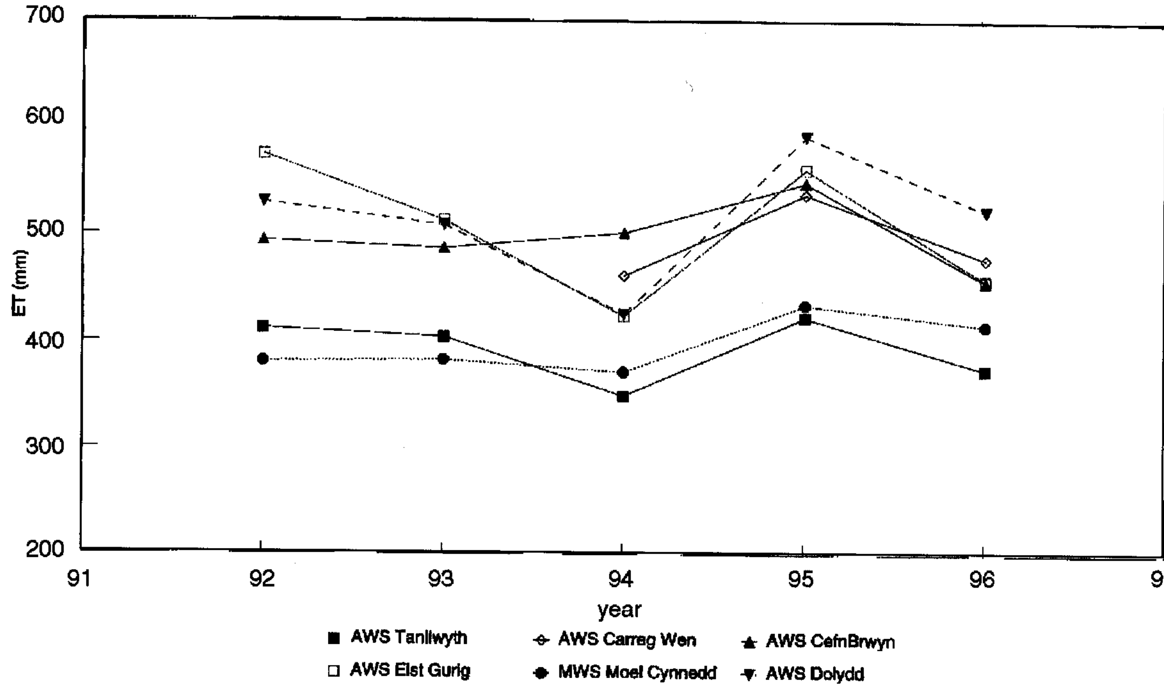

Fig. 14. *Comparison of annual E_t estimates for the manual met. site at Moel Cynnedd with AWSs at Tanllwyth & Carreg Wen (Severn), and Cefn Brwyn & Eisteddfa Gurig (Wye).*

Wen (570 m) in the Severn, and at Cefn Brwyn (359 m) and Eisteddfa Gurig (529 m) in the Wye. The years used for this analysis (1992–96) were chosen for consistency of data recovery, afforded by the increased reliability and ease-of-use of the latest data logging systems.

Figure 14 indicates a strong agreement in annual E_t between the manual climate station (MWS) and AWS Tanllwyth, which occupy different positions in the same forest clearing site at Moel Cynnedd. The current close agreement is mainly due to the convergence of the AD terms in recent years as the relative wind exposure of the two stations becomes more similar. There is also a significantly greater difference between the forest clearing site and any of the three sites on open grassland, than there is between the individual grassland AWSs or between the Moel Cynnedd stations (Table 5). Year to year patterns of variation are generally similar, driven by the dominant EB term (solar input), although the Moel Cynnedd sites may be suffering noticeably lower radiation because of topography, especially at times of low solar declination.

Excluding areas of the catchment with extreme topographical shelter, solar radiation levels will approximate the regional average (Harding, 1979) and it follows that spatial variation in E_t will be the result mainly of variations in the AD term. For stations on the open hillside, therefore, AD will represent a greater proportion of E_t than in sheltered locations. This is confirmed by the two-year mean (1992–93) AD/E_t ratio for Cefn Brwyn AWS of 31%, compared with the 23% at AWS Tanllwyth for the same period (Table 6). This translates to 154 mm yr^{-1}

Table 5. Relationships between E_t values from the Moel Cynnedd manual climate station, the Tanllwyth AWS and the AWSs in the Wye catchment.

Year	AWS Cefn Brwyn/ Tanllwyth	AWS Eisteddfa Gurig/ Tanllwyth	Manual Cefn Brwyn/ Moel Cynnedd	Manual Eisteddfa Gurig/ Moel Cynnedd
1992	1.20	1.39	1.30	1.51
1993	1.21	1.27	1.28	1.34
1994	1.44	1.22	1.35	1.14
1995	1.30	1.33	1.26	1.29
Mean	1.29	1.30	1.31	1.32
Wye Mean	1.29		1.31	

Table 6. Component terms (Energy Budget 'EB' and Aerodynamic 'AD') compared to annual E_t total (mm) for two Automatic Weather Stations (AWS) under conditions of differing exposure.

	AWS Tanllwyth			AWS Cefn Brwyn		
YEAR	E_t	EB	AD	E_t	EB	AD
1992	432	331	101	518	355	163
1993	422	329	93	479	329	144
Means	427	330	97	499	342	154
Ratio to E_t		0.77	0.23		0.69	0.31

compared to 97 mm yr^{-1}, and represents a 59% greater aerodynamic effect on open hillsides.

A detailed investigation into the nature of the differences between AWS sites is required, along the lines of that carried out on the AWS network at Balquhidder, Scotland (Blackie & Simpson, 1993). It seems likely that a combination of exposure and altitude may explain the differences in E_t between sites, particularly their effect on the aerodynamic term. In order that a more realistic spatial model of E_t can be developed, further work is required to define the reasons behind the observed spatial variation in E_t, in particular the identification and quantification of the major physical controls on the input climatic variables.

Conclusions

Analysis of data from the Moel Cynnedd manual climate station at Plynlimon has shown that changes in site characteristics over the 1969–1995 study period, mainly due to local forest growth and clearfelling, have had a greater influence on most individual climate variables, and consequently on the calculated potential evaporation, E_t, than has any trend in the climate. Only minimum air temperature displays evidence of long term change that cannot be wholly attributed to site factors, as the observed increases are greater than the standard deviation of values around the least squares trend line. In addition there is no obvious change either in gradient or the direction of the trend around the onset of clearfelling in 1985.

It can be concluded that climate sites within forest plantation clearings are not the best places to look for definitive proof of subtle regional or global climate changes, because they can be hidden by the inevitable changes in instrument exposure over the inherently-dynamic forest vegetation cycle. Nevertheless, the Moel Cynnedd record represents one of the longest running and most reliable indices of climate in the uplands. The advantages of continuity, completeness, relatively consistent instrumentation and methodologies, and intensive ongoing quality control, outweigh any perceived disadvantages caused by the choice of site. With further work, it may become possible to quantify retrospectively a 'coefficient of site exposure', use of which could identify and eliminate local effects and so quantify any underlying climate changes.

In spite of this limitation, the variability in the E_t estimate at Moel Cynnedd ($\sigma = \pm 25$ mm) has been small (±6%) relative to its mean absolute magnitude (393 mm yr^{-1}), so it still represents a useful index of potential moisture transfer to compare with catchment water balance estimates of evaporation, and to incorporate in predictive evaporation and streamflow models for ungauged catchments. The absolute magnitude of E_t, and its year-to-year variation, is dominated by the solar energy input term (74%).

Annual E_t calculated for the specific conditions of the Moel Cynnedd met. site, either from the manual data or the AWS, can never be truly representative of the surrounding catchments. Improving the spatial discrimination of E_t is an important future objective of the Plynlimon catchment studies, which has at least been started during this current analysis of data from the AWS network. In spite of the difficulties of obtaining a reliable and complete record from these remote automatic stations, concurrent runs of complete data indicate that E_t can be ~30% higher on exposed grassland sites than in the forest clearing. This is mainly due to a combination of exposure and altitude effects, manifest as variability in the aerodynamic term. The aerodynamic term on average contributes only 23% of E_t at the sheltered Moel Cynnedd site, largely due to low wind speeds, but AWSs on more exposed hillsides have been shown to record 59% higher AD. Moel Cynnedd E_t has a further limitation as a hydrological index, in that it can never represent the meteorological dynamics above the canopy that drive transpiration and interception losses from the surrounding forest that covers some 68% (pre–1985) of the Severn.

The way forward in improving catchment E_t estimation is to define short term relationships between the sites represented by the existing AWS networks with the MWS base station, and to use these 'inter-domain' relationships within a GIS framework to compute catchment E_t on an areal basis. More information on the climate above typical forest areas would also aid treatment of the hydrology of the forested portion of the Severn.

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