Has the Priestley-Taylor Equation Any Relevance to Forest Evaporation?

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ABSTRACT

Long-term evaporation measurements are expressed in the Priestley-Taylor (1972) "potential evaporation" framework for a spruce forest in Plynlimon, Wales, and a Scots Pine forest in Norfolk, England. The results are used to illustrate the possibility of significant variability in evaporation from forest vegetation in response to precipitation input, and so provide a warning against the indiscriminate use of the Priestley-Taylor formula. A tentative suggestion is made regarding a possible role for potential evaporation in the forest environment.

1. Introduction

Penman (1948) demonstrated that in the absence of any control at the earth's surface, evaporation depends only on meteorological conditions. The particular combination of meteorological parameters can be considered the basis of a metric, used to relate evaporation measurements made at different locations and in different conditions by allowing for the variation due to this meteorological control. In an attempt to provide a more convenient metric, Priestley and Taylor (1972) simplified the Penman equation by redefining potential evaporation E_p as

$$E_p = \frac{\alpha}{\lambda}\frac{\Delta}{\Delta+\gamma}(Q^* - G), \qquad (1)$$

where α is a constant, Q^* the net radiation, G the soil heat flux, Δ the gradient of saturated vapor pressure with temperature and γ the psychrometric constant. Using this expression with data gathered from several different oceanic and saturated land surfaces, these authors found that the actual evaporation E_a could be simply equated to potential evaporation,

$$E_a = E_p, \qquad (2)$$

with the constant α in the order of 1.2–1.3. Several other evaporation data sets have since been similarly expressed (e.g., McNaughton and Black, 1973; Davies and Allen, 1973; Thompson, 1975; Stewart and Rouse, 1977; Mukammal and Neumann, 1977), tending to reinforce the use of Eq. (2), with a value of $\alpha = 1.27$, as a means of estimating actual evaporation in potential conditions.

The overall effect of this work is to perpetuate and propagate the idea that actual evaporation, when averaged over several days or weeks, is a simple and easily calculable function of temperature and radiant energy, independent of precipitation input and only weakly related to vegetation cover. The validity and usefulness of Eq. (2) as a practical description of surface evaporation flux for use in large-scale meteorological applications is not the concern of this paper. The authors are concerned that the indiscriminate use of the Priestley-Taylor hypothesis generates complacency regarding the importance of "surface" control in the evaporation process, and that this complacency might be transferred from the meteorologist to the hydrologist and water engineer who, tempted by computational convenience, will adopt it as a universal description of evaporation loss.

This paper compares estimates of potential evaporation using the Priestley-Taylor equation with two measured evaporation data sets for tall (forest) vegetation. The comparison is made both when water is freely available on the surface of the vegetation, and in conditions of transpiration when at least one of the forests represents "potential" conditions in the, perhaps erroneous, but often accepted sense that there is no significant soil moisture stress. The object is to provide general evidence on the variability of evaporation, and in particular to provide evidence on the divergence of forest evaporation from the Priestley-Taylor metric. An attempt is made to provide a nonpredictive but concise description of these data by developing an equation which contains some elements of the Priestley-Taylor metric but which acknowledges the primary change in surface status, that between wet and dry conditions.

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2. Experimental data

The data sets used in this analysis are extensive evaporation measurements for two mature forest stands in the United Kingdom. The experimental sites are located in the extreme west and east of the country and therefore might be considered indicative of the change in evapotranspiration for this vegetation type in response to a precipitation difference of the order of 1800 mm year^{-1} between the sites.

a. The Plynlimon data set

The data set consists of simultaneous measurements of evaporation and meteorological variables extending on a continuous basis from February 1974 to September 1976. The experimental site, at Plynlimon, Powys, central Wales, is located close to the center of the Institute of Hydrology's experimental catchment (Clarke and McCulloch, 1976), which is extensively forested with Sitka and Norway Spruce.

The evaporation measurements were made with a "natural" lysimeter described by Calder (1976), containing a sample of 26 trees. The representativeness of the lysimeter has been established by comparison with the total evaporation loss from the whole catchment (Calder, 1976); while successful modeling of the detailed variation in measured evaporation in terms of a physically based model (Calder, 1977) gives increased confidence in the experimental data. In parallel with this lysimetric measurement of total evaporation loss, a separate measurement was made of the loss due to rainfall interception by the forest (Calder and Rosier, 1976).

For the early part of the experiment the meteorological variables used in calculating the Priestley-Taylor definition of potential evaporation were measured on a routine basis with a pair of automatic weather stations (Strangeways, 1972) located in a small grassland clearing 400 m from the lysimeter. During this period the net radiation into the forest was estimated by multiplying that measured over grass by 1.1; this average correction factor was obtained as part of a separate study (Roberts, 1977, private communication), and validated by the installation of a single, automatic weather station above the forest canopy, which was used as the primary measurement during the latter part of the experiment.

No measurements of soil heat flux were available at Plynlimon; however, soil heat flux is low beneath a forest—usually a negligible part of the total energy budget (Sinclair *et al.*, 1975). For the purpose of this study, in which evaporation losses are calculated over long periods, the integrated heat flux is assumed negligible.

b. The Thetford data set

Precise measurements of evaporative and meteorological variables were gathered, as part of an extensive study of forest micrometeorology, on a discontinuous basis over the period 1972–76. Several examples of the use of these data already exist in the literature, as do descriptions of the experimental apparatus and analysis techniques used (e.g., Oliver and Oliver, 1973; Stewart and Thom, 1973; Gash and Stewart, 1975; McNeil and Shuttleworth, 1975; Thom *et al.*, 1975). The experimental days were selected on the basis of operational convenience irrespective of meteorological conditions from spring to autumn: while they might be considered a "random" sample of measurements of evaporation over the periods of the field study, it should be remembered that such field studies were not carried out in winter, so that the resulting data are only truly representative of spring, summer and autumn conditions. Measurements of the evaporative loss by rainfall interception, however, are available separately all year round (Gash and Morton, 1978).

Evaporation was determined by the energy budget/Bowen ratio method with gradients of temperature and humidity measured above the forest with accurate, quartz-crystal psychrometers (Gash and Stewart, 1975) arranged as profiles (Stewart and Thom, 1973) until 1973, and used in a thermometer interchange system (McNeil and Shuttleworth, 1975) since that time. The meteorological parameters required to compute potential evaporation were available as part of the data necessary for the evaporation measurement. Only days with continuous data extending at least from dawn to dusk were used in this study: data were more usually available for the complete 24 h period. In total 198 days of data were used from this data set.

3. Results

The comparison between actual measured evaporation and that calculated from Eq. (2) with $\alpha=1.27$ is presented in Fig. 1 as cumulative sums for days of experimental data. The beginning and end of successive years are marked to give an indication of time of collection and amount of data available for each year. The separation into wet and dry periods in this diagram is not meant to be definitive, merely instructive; it was made for the Plynlimon data on the basis of the occurrence of rainfall during the preceding 3 h, and for the Thetford data on the basis of in-canopy wetness sensors (Stewart, 1977). It should be remembered that the Thetford data consists of discontinuous daily samples with a seasonal frequency distribution biased toward summer conditions, hence the preponderance of dry canopy data. The results presented are *not the cumulative evaporation loss from Thetford forest for complete years.*

The calculation of potential evaporation was carried out on an hourly basis *for daylight hours* (net radiation positive). This decision reflects the inconsistent availability of nighttime data in the Thetford data set, and a desire to make the most favorable comparison possible

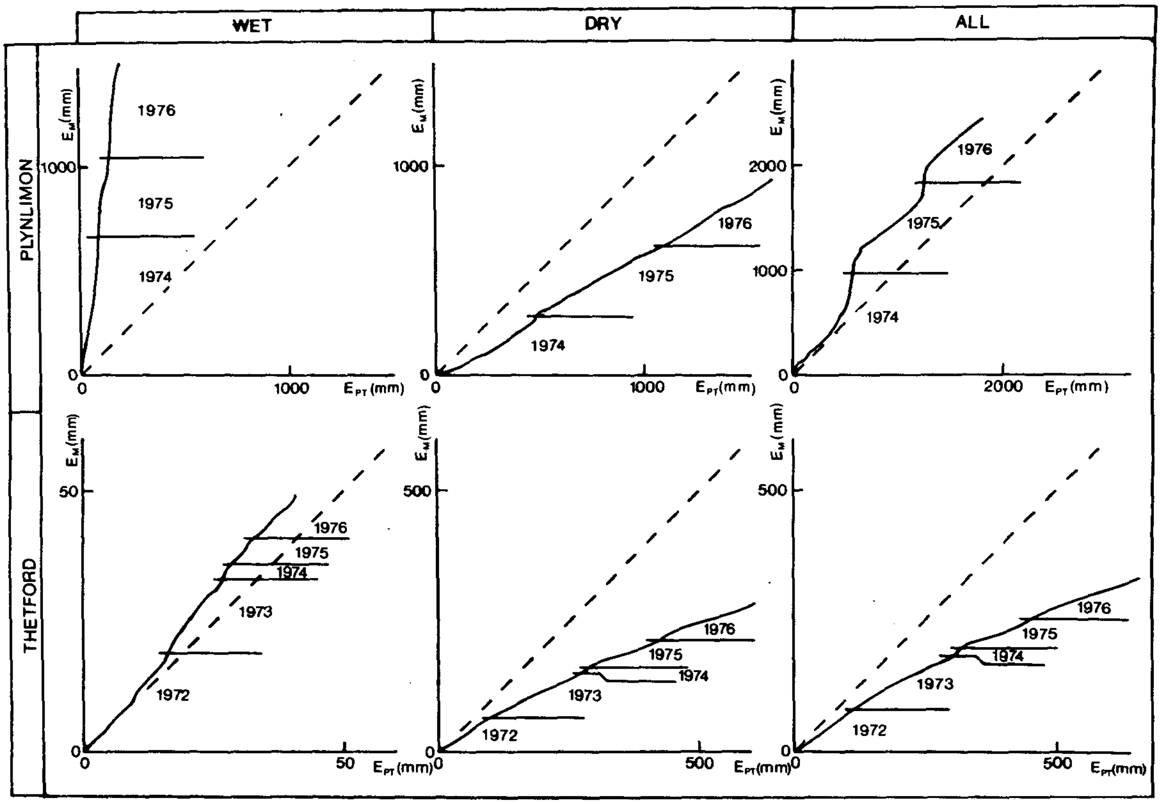

FIG. 1. Comparison between measured evaporation E_M and E_{PT} calculated from Eq. (2) with $\alpha = 1.27$, expressed as cumulative sums over the several years of data collection for the Plynlimon and Thetford evaporation data sets. A separate comparison is made for both wet and dry periods, and for the total loss in all conditions. (Note. The results given for Thetford are *not* the cumulative evaporation loss for complete years.)

with the Priestley-Taylor prediction. The predictive ability of Eq. (2) is best in the absence of advective effects; at night systematic sensible heat advection occurs routinely to maintain the outward net radiation flux. In general, the evaporation process plays a minor role in the total energy transfer at night, and a radiation-based evaporative flux prediction would be less likely to have validity in such conditions. Estimates were made of the effect of restricting the calculation to daylight hours for the two data sets; including the (negative) nighttime contribution reduced the cumulative prediction given by Eq. (2) by about 10–15%, worsening the comparison for the Plynlimon site and improving it for the Thetford site by this amount.

4. Discussion

Although attempts were made to optimize the comparison by removing nighttime periods with sensible heat advection, no attempt was made to restrict the comparison further to daylight periods with zero advection, nor was attention given to soil wetness. In their original work Priestley and Taylor (1972) drew attention to the limited descriptive power of Eq. (2) in advective conditions and over unsaturated soils. Although some attention has since been paid to the importance of soil moisture as a surface control (e.g., Mukammal and Neumann, 1977), less attention has been given to the possibility of long-term, medium-scale advection.

We make no apology for refusing to impose restrictions on these data to further optimize the agreement between measurement and the Priestley-Taylor prediction. It is the essence of our thesis that for tall vegetation, with large atmospheric exchange coefficients, the extent of the control on evaporation exerted by the surface wetness status is considerable, and that meteorologically based evaporation metrics such as those of Priestley-Taylor or Penman, which pay minimal attention to surface conditions, are of limited use. It is apparent from Fig. 1 that in both these data sets, the status of the surface (whether it is wet or dry) is the primary control on evaporation rate. When the vegetation is dry, physiological control systematically reduces the evaporation rate below that predicted by the Priestley-Taylor equation even when no soil moisture stress is present, as demonstrated by the Plynlimon data. In fact, Calder (1978) found no evidence of an additional reduction in evaporation rate in response to the soil moisture deficits of 200 mm (corresponding to soil tensions of 6 bars) observed at this site in the drought of 1976. When the vegetation

TABLE 1. Effective values of α in Eq. (1) relating total measured evaporation for the two forest evaporation data sets.

Location and year		Wet conditions	Dry conditions	All conditions
Plynlimon,	1974	9.33	0.74	2.08
	1975	8.57	0.73	1.44
	1976	11.52	0.76	1.69
	All	9.69	0.74	1.72
Thetford,	1972	1.44	0.81	0.89
	1973	1.79	0.62	0.67
	1974	(1.76)	(0.95)	(1.04)
	1975	1.55	0.50	0.53
	1976	1.16	0.62	0.64
	All	1.50	0.64	0.69

Notes: These values only apply to the sample of daily evaporation measurements used in this analysis: the Thetford data set in particular has a strong sample bias toward the middle of the year.

The 1974 Thetford data are limited and the values of α less reliable than for other years.

is wet, the complete removal of all surface control means that it is possible for the evaporation process to exploit the large atmospheric exchange coefficients and obtain access to the considerable sensible heat already stored, or presently being released by the precipitation process, in the lower levels of the atmosphere.

It is quite possible that meteorologists unfamiliar with forest micrometeorology, in general, and these data, in particular, might be surprised by the routine and long-term observation of sensible heat advection to a wet forest. The conventional attitude, that evaporation is largely a radiation-controlled process, is of course easily justified for short vegetation from more fundamental descriptions such as those provided by Monteith (1965) or Shuttleworth (1976, 1978). At the same time and on the same basis, it is also fairly easy to understand why evaporation from tall vegetation, with large atmospheric exchange coefficients, is more intimately related to the atmospheric vapor pressure deficit (e.g., Stewart and Thom, 1973; Thom and Oliver, 1977). Indeed, for basic theoretical reasons, the simple experimental observation of a finite atmospheric humidity deficit near the surface of forest vegetation in wet canopy conditions very often implies the presence of sensible heat advection, since the incident radiation is often low at such times.

The Plynlimon data presented here are particularly useful in demonstrating an extreme example of large-scale, medium-term advection. In wet canopy conditions the surface obtains typically only 20% of its total energy input in the form of radiant energy; indeed, the effect is so large that even when averaged over several years, the total evapotranspiration loss from the forested area is approximately 12% higher than the total radiant energy input.

An explanation of the process which allows such large-scale energy advection may be provided by consideration of the meteorological conditions which normally prevail during wet conditions. At Plynlimon, as with most upland forested catchments in the United Kingdom, the most common type of rainfall is that brought about by frontal activity. This activity is generally associated with a well-mixed, deep boundary layer which has a large transverse wind speed, typically 20 m s^{-1} (see e.g., Browning *et al.*, 1975). Under such conditions the interactive feedback between the air mass moving over a wet forest of medium size (~10 km) and the evaporation flux is slight. Air movement over forests with dimensions of the order of 100 km would be necessary before the cooling and humidification of the boundary layer was sufficient to significantly reduce evaporation rates. In fact, such simple horizontal air movements probably rarely occur over these distances because the latent heat released by condensation in clouds is associated with large-scale ascent, thereby producing an effective sink for the cold moist air. Indeed, the mechanism of frontal rainfall can only be maintained by rapid advection in response to this vertical motion.

Clearly, with tall vegetation the behavior of the whole planetary boundary layer is important and it could be dangerous to base the prediction of *total* evaporation loss merely on empirical relationships with radiation, temperature and soil moisture status. Such an approximate empirical relationship may be possible as a rather approximate estimator of (dry canopy) transpiration; indeed, on the basis of Fig. 1 and Table 1, the present data might suggest the use of Eq. (1) in the form

$$E_T \approx (0.72 \pm 0.07) \frac{\Delta}{\lambda(\Delta+\gamma)} (Q^* - G) \tag{3}$$

as a long-term, first-order estimate of this *component* for both forests, the value of α being the mean and standard deviation of the yearly values weighted by the number of "data days" available. However, the total evaporation loss also depends critically on the frequency and duration of precipitation and in particular on the fraction lost as a result of interception by the forest canopy. Forest evaporation can therefore be almost as variable as precipitation.

In a recent paper Thom and Oliver (1977) have attempted to modify the original Penman approach to take account of differing vegetation types, and the modification of surface control in response to precipitation amounts. However, Gash (1978) has pointed out that their approach, in fact, is equivalent to expressing actual evaporation E_a as

$$E_a = E_T + I(1 - C_T), \tag{4}$$

where E_T is a physically realistic transpiration estimate and I the interception loss. The term C_T is a correction to take account of the fact that the transpiration estimate is also made while the evaporation of intercepted water is still in progress. Its value has been calculated as 0.07 for Thetford Forest (Gash and Stewart, 1977).

It is obviously also possible to attempt a similar modification of the Priestley-Taylor metric by using Eq. (3) as an upgraded estimate of forest transpiration. Within this last assumption the value of C_T for Plynlimon is given as the ratio (α_D/α_W), where α_D is the value of α [Eq. (1)] in dry conditions and α_W the value in wet conditions, for the Plynlimon data. It can be seen from Table 1 that C_T is again approximately 0.07, and Eq. (4) can therefore be rewritten in the form

$$E_a \approx (0.72 \pm 0.07) \frac{\Delta}{\lambda(\Delta+\gamma)} (Q^* - G) + 0.93I \qquad (5)$$

as a first-order description of these data.

It is possible that Eq. (5) might be of some predictive use in high rainfall areas, given a physically based, predictive model of the interception component such as those of Rutter (Rutter *et al.*, 1971) or Gash (1979). In such conditions the total evaporation loss is less sensitive to the empirical transpiration estimate. The predictive use of Eq. (5) in dry areas, where transpiration is the major loss, is limited by its empirical content.

It is possible to develop Eq. (5) further, with an additional rather dramatic decrease in its predictive accuracy. Gash (1979) has created an analytic model of forest interception based on physical principles similar to those used in the numerical model of Rutter *et al.* (1971). In so doing he demonstrates that there is at least some physical justification for expressing the interception loss from a forest in terms of a regression on precipitation input, *but* that the regression coefficients are likely to be variable because they depend on the mean rainfall rate and mean wet canopy evaporation rate for the particular location, and the structure of the particular canopy. Direct measurements of interception in these two forests (Calder, 1976, 1977; Gash and Stewart, 1976; Gash and Morton, 1978), summarized in Fig. 2, suggest a rather approximate relationship of the form

$$I \approx (0.29 \pm 0.08)P, \qquad (6)$$

where P is the precipitation input.

In the Priestley-Taylor framework, therefore, the equation which gives a first-order approximation to evapotranspiration in rough (20%) agreement with the long-term, *total* evaporation loss for the two forests considered in this paper has the form

$$E_a = (0.72 \pm 0.07) \frac{\Delta}{\lambda(\Delta+\gamma)} (Q^* - G) + (0.27 \pm 0.08)P. \qquad (7)$$

No claims are made for regarding the predictive ability of this empirical expression outside the experimental data on which it is based. The suggested errors are probably only realistic when describing medium-term average evaporation; the expression is rather a poor description of short-term evaporation loss and is there-

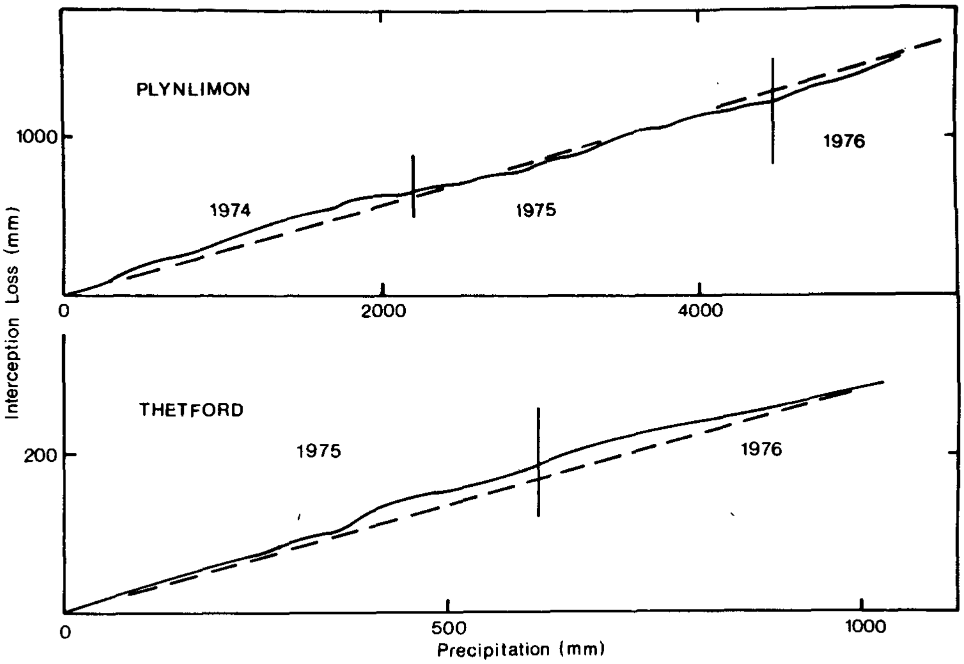

FIG. 2. Cumulative loss of water, as a result of rainfall interception by the forest canopy, expressed in terms of cumulative precipitation input for coniferous forest in Plynlimon and Thetford. The dashed line represents the relationship $I=0.29\,P$ in both cases.

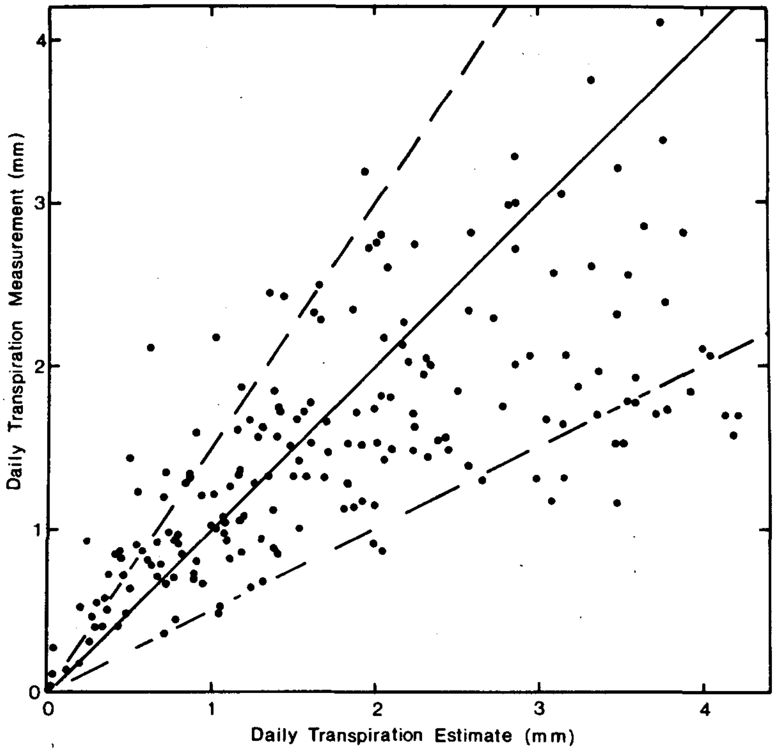

FIG. 3. Comparison between the daily measurement of evaporation made over Thetford Forest compared with a daily estimate made using Eq. (3) in the text. The full line represents equality, the dashed lines a variation of 50% around equality.

fore unlikely to be of much use in short-term management. This is apparent in Fig. 2, as variations in the relationship between interception and precipitation. But it is more obvious in Fig. 3, which is a comparison between a daily transpiration estimate, given by Eq. (3), and measured daily transpiration for Thetford Forest. (The lysimetric measurement used in the Plynlimon data does not permit a similar comparison for that data set.) In the light of this short-term variability, the value of $\alpha=1.05$ found by McNaughton and Black (1973) from 16 dry days of evaporation data, collected over Douglas fir in British Columbia, clearly cannot be regarded as inconsistent with these data; particularly since their value is based on a 24 h comparison. For the reasons outlined earlier the value of $\alpha=0.72$ reported here is the long-term average value based on a daytime comparison; the value deduced from a 24 h comparison would be in the order 10–20% higher, depending on overnight cloud conditions and the amount of sensible heat advected to maintain the night time radiation loss.

Eq. (7) does provide at least a *working description* of the long-term total evaporation loss for both sites as illustrated in Fig. 4, which makes a comparison between measured evaporation and that calculated using this equation. The dashed line indicates equality, while the dotted lines indicate the estimated errors expected for a description using this expression. The agreement for the Plynlimon data set is obviously much closer than that for the Thetford data set. This reflects, in part, the fact that the empiricism implicit in Eq. (7) is biased toward Plynlimon because that is where the weight of data lies; and in part, the fact that a greater fraction of the evaporation from Thetford occurs as the more variable transpiration component. It is probably worth pointing out that most of the shortfall in measured evaporation from Thetford occurs in the summers of 1975 and 1976, within an 18-month period which was the driest on record in the United Kingdom.

5. Concluding remarks

This paper makes no comment on the relative merits of the Priestley-Taylor and the Penman formulas as a basis for evaporation prediction: the two seem to have some conceptual similarity and often produce numerically similar results (at the 5–10% level), but the Priestley-Taylor version is easier to apply. Neither do we suggest the alternative use of Eqs. (5) or (7) as a generally valid description of forest evapotranspiration. Indeed, we reiterate our warning against the indiscriminate use of any simplistic equation with a large empirical content in this application. Eq. (7) does provide at least a reasonable long-term description of the two rather different forest evaporation data sets

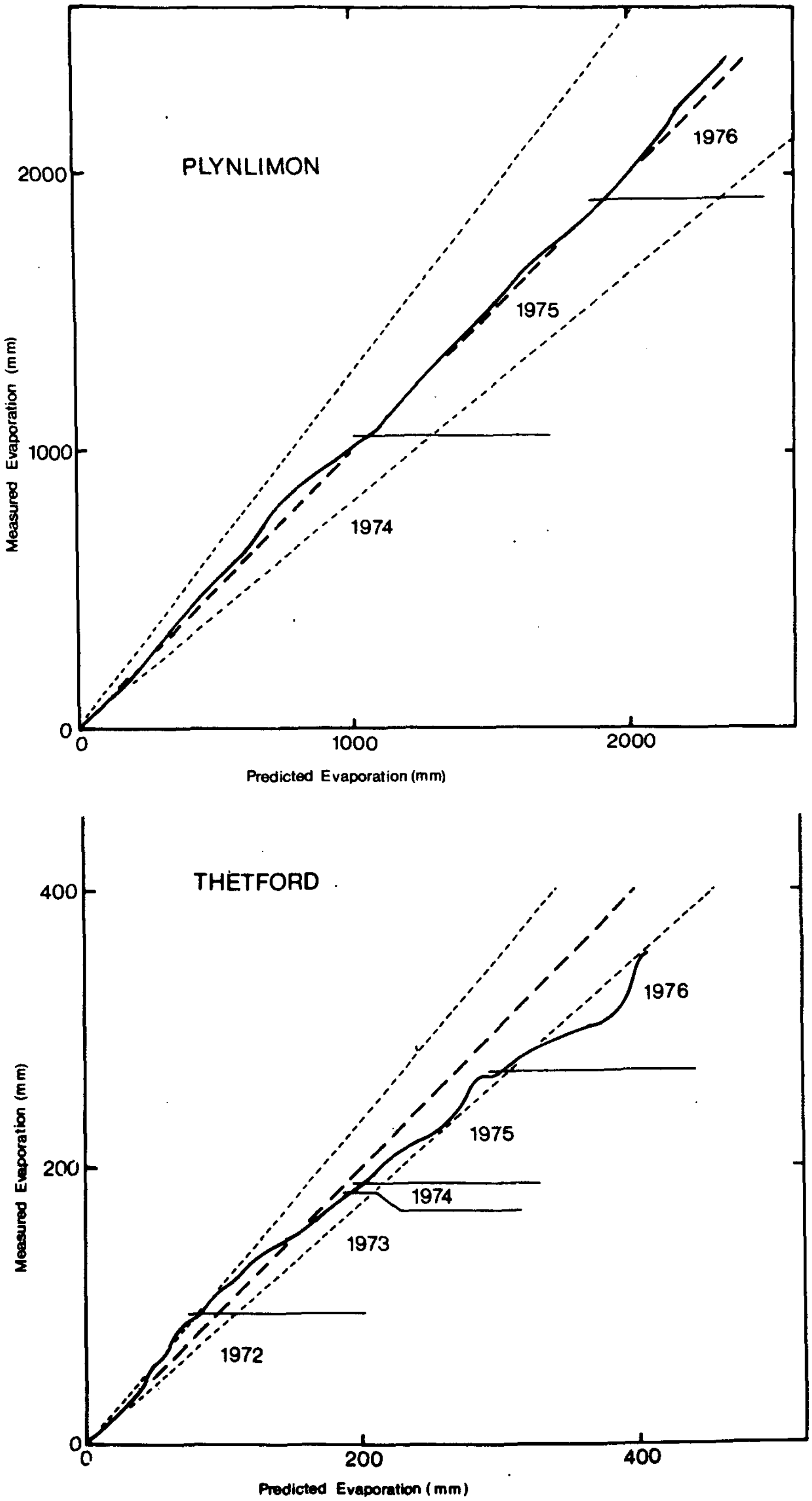

FIG. 4. Comparison between measured evaporation and a calculation based on Eq. (7) for the Plynlimon and Thetford data. The long-dashed line represents equality, the short-dashed lines indicate the expected errors.

presented here—something which is not possible using the simpler Priestley-Taylor metric.

It remains our fundamental belief that evapotranspiration in general, and forest evapotranspiration, in particular, are processes subject to physical and physiological control; and that the laws of physics are not influenced by human desire for computational simplicity. Our purpose is to make explicit the possible variability of forest evaporation as a result of its close dependence on surface controls and the real possibility of medium-scale, long-term advection in high rainfall areas.

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