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To cite this version:

M. N. Hough, R. J. A. Jones. The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0-an overview. Hydrology and Earth System Sciences Discussions, 1997, 1 (2), pp.227-239. hal-00304391

HAL Id: hal-00304391

https://hal.science/hal-00304391v1

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Hydrology and Earth System Sciences, 1(2), *227–239* (1997) © EGS

Hydrology & Earth System Sciences

The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0—an overview

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Abstract

The operational system known as MORECS which provides estimates of evaporation, soil moisture deficit and effective precipitation under British climatic conditions has been revised as version 2.0. An overview of the new system is described with emphasis on the new additions. The major changes from the older version (Thomson, Barrie and Ayles, 1981) include the introduction of the crop oil-seed rape, a revised treatment of soils and available water capacity and a land use data base which is representative of the 1990s.

Introduction

MORECS, an acronym for the UK Meteorological Office Rainfall and Evaporation Calculation System, was introduced in 1978 (Thomson *et al.* 1981) as a replacement for the Estimated Soil Moisture Deficit (ESMD) bulletin first issued by the Meteorological Office about 15 years earlier. MORECS underwent an extensive revision in the winter of 1980/81 and the version which was introduced in summer 1981 continued virtually unchanged until 1995. The MORECS which was operational between 1981 and 1995 is called version 1.0, while the revision produced in 1995 is considered as version 2.0.

Since 1981 considerable changes have taken place in the agricultural industry and new soil and land cover databases have become available. The cropping patterns incorporated in MORECS 1.0 are relevant to the situation in the 1960s but, by the early 1990s, the area of winter cereals had increased, mainly at the expense of spring barley, the area under grass had been reduced and oil-seed rape had become the third most extensive crop in the UK. At the same time, the Common Agricultural Policy of the EU had introduced the set-aside policy aimed at reducing the area of land under cereals. The availability of computerised soil databases offered MORECS access to the soil data for calculations of actual soil moisture. Within this revision much of the basic science remains unaltered, but other aspects have been revised with some completely new additions (Table 1).

In this paper, the version of MORECS which produces output on a grid square format (40 km × 40 km) is described, though a single-site version of MORECS is also available (using rainfall from a single raingauge with on-site or nearby climate data).

MORECS uses daily synoptic weather data to provide estimates of weekly and monthly evaporation and soil moisture deficit, in the form of averages, over 40 km × 40 km

Table 1. Comparison summary of MORECS 1.0 and 2.0

Factor	MORECS 1.0	MORECS 2.0
Land use	Typical of 1960s	Typical of 1990s including oil-seed rape, set-aside, forestry area from satellite data, revised urban areas.
Soils	High, medium, low available water is standard everywhere	Measured soils data used to find range of AWC in each square. Scotland and N Ireland found by analogue with England and Wales squares.

Note: AWC is the available water capacity in the rooting range for the crop and soil combination.

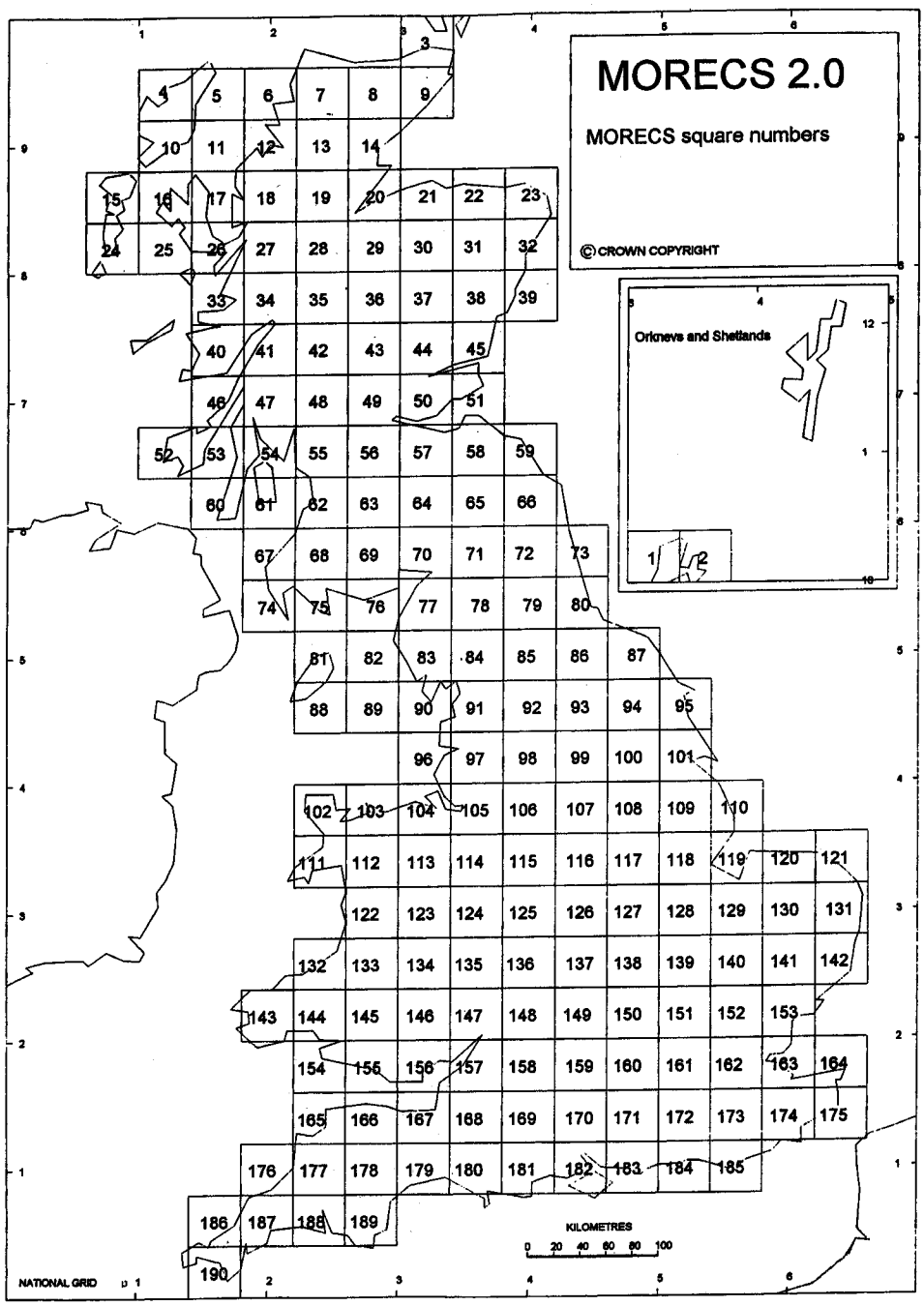

Fig. 1 *A map showing the square numbering in MORECS.*

squares aligned with the National Grid of the UK Ordnance Survey over Great Britain (Fig. 1). Prompt provision of this information can assist a variety of users; for example in the assessment of catchment water balances, the leaching of nutrients and short-term irrigation requirements.

Outline description of the system

COMPONENTS OF THE SYSTEM

Data collection, interpolation and processing

Daily values of the meteorological variables, namely hours of bright sunshine, air temperature, vapour pressure, wind speed and rainfall, are available in the Synoptic Data Bank at the Meteorological Office Headquarters at Bracknell.

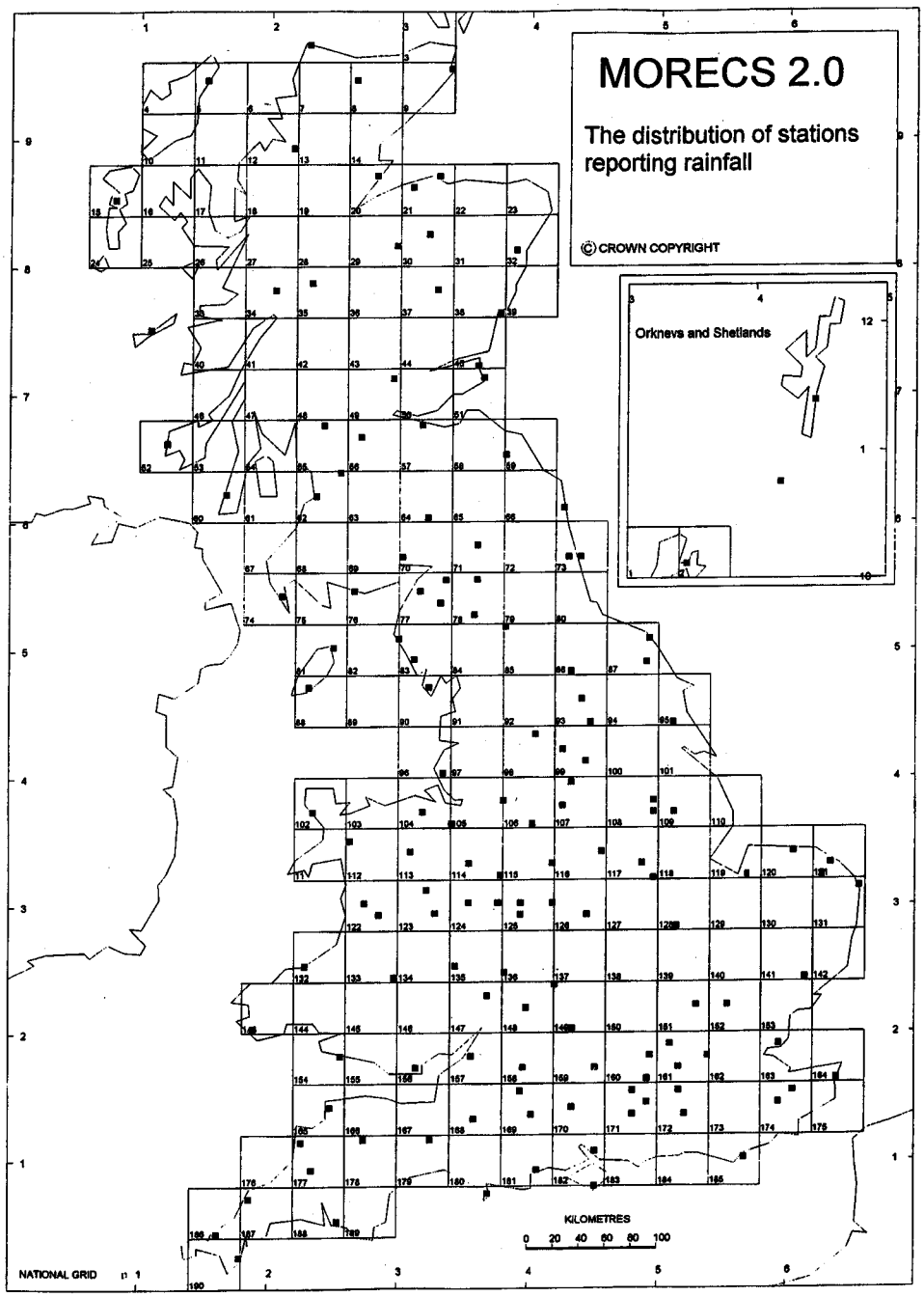

Fig. 2 *A map showing the stations which report daily rainfall.*

Fig. 2 shows the distribution of rainfall stations. Many of these also supply temperature, wind and vapour pressure data, but only about half report sunshine hours. Objective interpolation is then used to obtain grid-square average values of each variable. The station data are first normalised or standardised as follows:

(i) Rainfall is expressed as a percentage of the annual station average.

(ii) Sunshine is converted to percentage of the average daily duration for the month.

(iii) Temperature and vapour pressure are 'reduced' to mean sea level, using lapse rates of –0.6 °C/100 m and –0.025 hPa/100 m respectively.

(iv) The wind speed, which is usually measured at 10 m above the ground, is converted to a value appropriate to a 'standard' site (one having a flat, uniform exposure

of short grass) using an empirical factor related to the general terrain roughness around each station.

Interpolation to obtain values for 40 km × 40 km squares is then carried out. The 9 stations nearest to the centre of each square are selected, irrespective of whether they have data, up to a maximum of 100 km from the centre. If there is a station within 0.5 km of the centre, then its observations are used alone. Otherwise, from the 9 stations selected, the 6 nearest ones with data are chosen, with the proviso that there are no more than 2 stations in each octant. If less than 3 stations are found, then an inverse distance squared method of interpolation is used. Otherwise plane-fitting is carried out (Shearman and Salter, 1975).

The errors involved in these interpolations are unlikely to be large for temperature and humidity, which usually change little with distance after conversion to mean sea level. Acceptable estimates of wind speed are usually obtainable. Greater difficulties are experienced with sunshine because the network of sunshine recorders is fairly sparse. Therefore, it is difficult to find, in every square, representative long term daily average values of sunshine duration. This is especially so where the square includes much high ground, because there is a general lack of upland measuring sites. It is, therefore, likely that values of sunshine duration will be overestimated for squares with large amounts of high ground because the sunshine average is based on sunnier lowland stations.

Rainfall shows large spatial variation, even over uniform terrain, especially in summer. Fairly reliable long term average annual rainfall can be calculated for each 40 km × 40 km MORECS square using data from the several thousand rainfall stations available. However, in the short term with only synoptic stations available, the square-average rainfall estimates could be misleading, so it is recommended that MORECS users evaluating inputs for irrigation scheduling should install their own raingauge.

No data averaging is performed with single site MORECS. In this case, the data are taken directly from a station and if any data are missing, values from nearby sites are used wherever possible.

Analysis to obtain evaporative demand over each square

Daily potential evapotranspiration (PE) is calculated for each grid square for a range of surface covers from bare soil to forest, using a modified form of the Penman-Monteith equation (Monteith and Unsworth, 1990).

$$\lambda E = \frac{\Delta(R_{ne} - G) + \rho C_p(e_s - e)(1 + br_a / \rho C_p) / r_a}{\Delta + \gamma(1 + r_{sc} / r_a)(1 + br_a / \rho C_p)} \quad (1)$$

where

E = rate of water loss (kg m^{-2}s^{-1})
Δ = rate of change of saturated vapour pressure with temperature (mb °C^{-1})
R_{ne} = net radiation, R_n calculated assuming the bulk surface temperature, T_0 is equal to the screen temperature T_{scr} (W m^{-2})
b = $4\varepsilon\sigma(273.1 + T_{scr})^3$ is a correction term such that $R_n = R_{ne} + C$, where $C = \varepsilon\sigma((273.1 + T_{scr})^4 - (273.1 + T_0)^4) \cong b(T_{scr} - T_0)$
ε = emissivity
σ = Stefan's constant
G = soil heat flux (W m^{-2})
ρ = air density (kg m^{-3})
C_p = specific heat of air at constant pressure (1005 J kg^{-1})
e_s = saturation vapour pressure at screen temperature (mb)
e = screen vapour pressure (mb)
λ = latent heat of vapourisation (= 2465000 J kg^{-1})
γ = psychrometric constant (= 0.66 for temperatures in °C and vapour pressure in mb)
r_{sc} = bulk surface (canopy) resistance (s m^{-1})
r_a = bulk aerodynamic resistance (s m^{-1})

Calculation of actual evaporation using a soil moisture extraction model

The PE estimates are converted to estimates of actual evaporation (AE), by progressively reducing the rate of water loss from the potential value to zero as the available water decreases from a fraction, p, of its maximum value to zero. This is done by increasing r_{sc} in Eqn. 1 according to

$$r_{sc} = r_{sc}(\text{min})(2.5/(1 - \text{BOTSMD}/(1 - p)\text{AWC}) - 1.5) \quad (2)$$

where r_{sc}(min) is the canopy resistance at no water stress, AWC is the available water capacity, i.e. the maximum quantity of water available to the crop and BOTSMD is the soil moisture deficit in the less easily available part of the AWC given by $(1 - p)$AWC. The value of p depends upon the soil-crop combination and ranges from 60% for bare soil to 25% or less for some crops and soils.

Calculation of water balance

The water balance (soil moisture deficit, SMD and excess precipitation, EP) is calculated daily. The difference between the actual evaporation and the rainfall, when added to the previous day's SMD, gives the current SMD. An EP value is calculated as the difference between evaporation and rainfall when the SMD = 0. A treatment of interception is included by calculating the proportion of the rainfall intercepted p^* as

$$p^* = 1 - 0.5^L \quad (3)$$

The interception is then p^*R where R is the daily rainfall and L is the leaf area index. However, the maximum interception capacity per unit leaf area is fixed at 0.2 mm so that the upper limit to interception is $0.2L$. In summer it is assumed that because of higher evaporation than winter and multiple rainfall events, the daily loss is twice the value calculated by p^*R, but not more than R. The evap-

oration of intercepted water (or dew) is estimated from Eqn. (1) with $r_{sc} = 0$.

These calculations are done under the various types of cropped surfaces, and also under the average land use for each square, using the relative proportions of the various surfaces. The average land use has been synthesised from MAFF census returns, satellite imagery and from MORECS 1.0.

Data output

The final stage is the production of maps and tables showing the grid-square weekly averages of the weather variables, PE, AE, SMD, stress (AE/PE) and EP for the various crops and real land use. The output is distributed by facsimile, but it is also possible to receive data by electronic mail and by post. A complete description of MORECS 2.0 may be found in Hough, *et al.* (1996).

Crop modelling

The crop models which are used in MORECS are idealised representations of crop growth. The models describe aspects such as plant development through the growth stages, leaf area index (to determine transpiration), crop height (for the aerodynamic resistance), the variation of the crop canopy resistance, r_{sc} with weather (for conifers) and crop age (cereals and oil-seed rape), and the changes in the available water capacity as roots grow in annual crops. The following sections consider each crop in turn.

GRASS

The leaf area index of permanent pasture is assumed to vary month by month as in Table 2. The height is assumed to be 0.15 m throughout the year. This is clearly a compromise between a well-grazed sward, which would be shorter and less leafy, and crops grown for hay or silage which would make more growth before being cut. The canopy resistance values reflect the effects of seasonal changes in temperature and light intensity and of leaf age (Table 3). Roots are assumed to be active throughout the year with old ones being replaced by young roots so that the water available to the crop remains constant.

WINTER WHEAT AND WINTER BARLEY

Crop development is by calendar date with fixed dates assumed for sowing, emergence, maximum leaf area and harvest in each square. The emergence date of 15th October in all squares is really a crop establishment date rather than true emergence which is usually earlier. A period of autumn growth is assumed from emergence to 1st December, after which growth is assumed to be static until a date in early spring when growth begins again. The leaf area index is as follows:

Table 2 Maximum values of leaf area index

Crop	Green leaf area index
Grass, riparian	2.0 (Jan), 2.0 (Feb), 3.0 (Mar), 4.0 (Apr), 5.0 (May), 5.0 (Jun), 5.0 (Jul), 5.0 (Aug), 4.0 (Sep), 3.0 (Oct), 2.5 (Nov), 2.0 (Dec)
Cereals	5.0
Oil-Seed rape	calculated in model, typically about 7.0
Potatoes	4.0
Sugar beet	4.0
Deciduous trees	6.0
Conifers	6.0
Orchards	5.0
Upland	3.5
Bare soil, rock, water & urban	0

Table 3 Daytime values of surface resistance (r_{sc}) for dense, green crops freely supplied with water. The value of 40 sm^{-1} used for most farm crops and is chosen between the values of 30 sm^{-1} for irrigated crops (Choudhury and Idso, 1985) and 50 sm^{-1} for 'well-watered' crops in Jamieson, Francis, Wilson and Martin (1995).

Type of crop	r_{sc} (s m^{-1})
Grass, riparian land	80(J, F), 60(M), 50(A), 40(M), 60(J, Jy) 70(A, S, O), 80(N, D)
Cereals	40
Potatoes, sugar beet	40
Oil-Seed rape	40
Deciduous trees	80
Conifers	70 (a)
Upland	160(O, N, D, J, F, M, A), 70(M, J, Jy, A, S)
Orchards	See text
Reference crop (b)	40
Bare soil	100
Water	0

(a) at zero vapour pressure deficit and 20 deg C.
(b) Reference crop is an idealised green crop which has constant properties throughout the year including the r_{sc} value

Winter wheat

$$\begin{aligned} L &= 0.25 && \text{(emergence to 1st December)} \\ L &= 0.50 && \text{(1st December to date of spring start)} \\ L &= 0.5 + (L_{max} - 0.5)(d - d_e)/(d_f - d_e) \ldots && d_e < d < d_f \\ L &= L_{max} && d_f < d < d_h \end{aligned} \quad (4)$$

Winter barley

$$\begin{aligned} L &= 0.5 && \text{(emergence to 1st December)} \\ L &= 0.9 && \text{(1st December to date of spring start)} \\ L &= 0.9 + (L_{max} - 0.9)(d - d_e)/(d_f - d_e) \ldots && d_e < d < d_f \\ L &= L_{max} && d_f < d < d_h \end{aligned} \quad (5)$$

where d_e, d_f, d_h refer to the dates of spring start, full leaf cover and harvest. L_{max} is the maximum leaf area index given in Table 2.

From emergence to the date of the spring start to growth, the crop height h is assumed to be 0.08 m. The subsequent variation is according to:

$$h = h_1 + (h_2 - h_1)[(d - d_e)/(d_f - d_e)]^2 \quad \ldots \; d_e < d < d_f$$
$$h = h_2 \qquad d_f < d < d_h \tag{6}$$

where h_1 is 0.08 m and the final height h_2 is 0.8 m. For well-watered crops, the effects of crop age on the bulk canopy resistance are included by writing:

$$r_{sc} = r_{sc}(\min) + 50\left(\frac{d - d_f}{d_h - d_f}\right) + 500\left(\frac{d - d_f}{d_h - d_f}\right)^3 \tag{7}$$

so that r_{sc} is large (about 600 sm^{-1}) at harvest.

The water available to the crop (AWC) is assumed to increase linearly from the bare soil value at emergence to twice this value by the end of autumn growth on 1st December. It then stays the same through the winter until spring growth starts after which it increases linearly to the date of maximum leaf cover. It then stays constant until harvest.

OIL-SEED RAPE

Oil-seed rape is introduced in MORECS for the first time in version 2.0 and the opportunity was taken to model the crop growth in a more dynamic way. Crop development, leaf area, crop height and the available water are described in terms of thermal time (temperature sums above a base temperature of 4 °C, rather than by date. MORECS assumes that the sowing date, in all squares, is the 1st September, but the subsequent growth depends mainly on temperature. The effects of vernalisation are allowed for by preventing the switch to reproductive growth and stem extension until mid-November at the earliest. During the winter period, the shorter days reduce the effectiveness of the thermal time. The model was constructed by reference to Mendham and Scott (1975), Evans and Ludeke (1987), Mendham *et al.* (1981), Evans (1981), Jenkins and Leitch (1986), Leach *et al.* (1989), Mendham *et al.* (1990).

SPRING BARLEY

The development from emergence to maximum leaf cover and harvest is by calendar date. The leaf area is given by:

$$L = (L_{\max} - 0.1)(d - d_e)/(d_f - d_e) + 0.1 \quad \ldots \; d_e < d < d_f \tag{8}$$

where the leaf area index is 0.1 at emergence and remains at L_{max} until harvest. The effects of senescence on the bulk canopy resistance are represented by Eqn. (7). The available water is assumed to be equal to that for bare soil at emergence and increases linearly to the maximum value when full leaf cover is reached. The height is assumed to be 0.05 m at emergence increasing according to Eqn. (6) to a maximum value of 0.8 m.

POTATOES AND SUGAR BEET

The root crops are planted or sown in spring and harvested in autumn. Leaf area development for the root crops is given according to Eqn. (8) with a constant value after the date of full leaf cover. The bulk canopy resistance without water stress is set to a constant value throughout the season. For potatoes and sugar beet, the available water increases linearly from that for bare soil at emergence to the maximum value when full leaf cover is reached. Both crops are assumed to be 0.05 m high at emergence with sugar beet reaching a maximum height of 0.35 m and potatoes 0.60 m.

DECIDUOUS TREES

The development of deciduous trees is described in terms of fixed dates for each square. From a date of bud burst, it is assumed that 40 days elapse before full leaf cover (LAI = 6) has been attained; similarly in autumn, leaves are assumed to take 40 days to fall off after the leaf fall start date. During the winter a bare soil situation is assumed. The foliation state has a marked effect on the wind profile which is represented by means of an 'effective' height. The effective height is assumed to be 2 m at bud burst and increases linearly to 10 m at full leaf cover. The bulk stomatal resistance with no water stress is equal to 80 sm^{-1} with leaves present, increasing to 180 sm^{-1} at the end of the leaf fall phase, but takes the bare soil value of 100 sm^{-1} during winter with no leaves. The available water capacity remains constant throughout the year.

CONIFEROUS TREES

Conifers are assumed to have a constant LAI = 6 throughout the year, a constant available water capacity and a fixed effective height of 10 m. Following Thompson *et al.* (1981), a temperature dependence for r_{sc} is represented by:

$$\begin{aligned} r_{sc} &= 25 r_{sc}(\min)/(T_{scr} + 5) \quad \ldots \; -5 < T_{scr} < 20 \\ &= r_{sc}(\min) \quad \ldots \; T_{scr} > 20 \\ &= 10^4 \quad \ldots \; T_{scr} < -5 \end{aligned} \tag{9}$$

where $r_{sc}(\min)(\delta e = 0)$ is found from Table 3 and the response to vapour pressure deficit δe is given by:

$$r_{sc} = r_{sc}(\delta e = 0)/(1 - 0.05\delta e^{(1-\delta e^2)0.0001333}) \tag{10}$$

where $r_{sc}(\delta e = 0)$ is found from Eqn. (9).

ORCHARDS

Orchards are assumed to go through the deciduous tree cycle of bud burst, full leaf cover, leaf fall and a winter

bare state according to a series of dates which are fixed for each square. Orchards are assumed to be largely grass-covered so that, in winter with bare trees, a grass model is used and, in the rest of the year, the grass properties of leaf area and bulk canopy resistance are combined with those for trees.

UPLAND AND SET-ASIDE

The upland land class represents much of the unimproved grassland which is typical of upland areas. Other vegetation types such as heather etc. may be present and there may be bare areas as well, but rooting depth is usually restricted by shallow soils or the presence of waterlogging. The growing season is typically short, while in winter growth is slow and there is usually much dead material present. The available water capacity is assumed to be half that for grass and the proportion which is freely available is taken to be the same as for grass. The canopy resistance value is assumed to be 70 sm^{-1} during the main growth phase from May to September (Lockwood, Jones and Smith, 1989), but increases to 160 sm^{-1} from October to April (Table 3).

As a result of the agricultural policies of the European Union, arable farmers are required to convert a portion of their land which grows cereals and oil-seed rape to a land use known as rotational set-aside. In addition, there is an option for set-aside outwith the rotational scheme. In MORECS, set-aside is represented by the upland land use.

WATER SURFACES

Evaporation from water is estimated from the Penman-Monteith equation assuming a canopy resistance of zero. In effect, the water is treated as a kind of soil with no allowance for heat storage as would occur with large and deep water bodies. Because of this, the estimates of water evaporation should be used only for water less than about 20 cm deep. For deeper water, the evaporation will be overestimated in Spring (as the water takes up heat) and underestimated in Autumn (as the water gives up heat). Evaporation from very small water bodies such as pans is likely to be underestimated in summer.

RIPARIAN

Some of the land around open water features, such as lakes and rivers, is assumed to have a permanent water table at shallow depth so that the vegetation (grass) has access to water at all times. The evaporation is assumed to be at the potential rate and, although the SMD is taken as zero, an EP value is calculated.

BARE ROCK AND URBAN

Small areas of mountainous country are classified as rock and it is assumed that all water is lost as runoff so that PE is ignored (with AE = 0) and with EP = rainfall. For urban areas, PE is calculated by assuming that the albedo is 0.1, the effective height is 15 m and the 'canopy' resistance is zero. However, the AE is limited to a maximum value of 0.5 mm which is assumed to be the 'AWC' of this land use. If there is no rainfall, then AE is zero. If the rainfall is between zero and 0.5 mm, then AE = rainfall.

Soil available water capacity (AWC)

The water in the soil that is available for plant growth has been the subject of wide-ranging research over the past three decades. There are inherent difficulties in estimating the amounts of water available for plant growth because of variables such as depth of rooting and the difficulties of simulating the process by which roots extract water from the soil. Early attempts at estimating available water were based on texture (Salter and Williams, 1965) but, Thomasson (1979) pioneered the measurement and use of water retention at fixed suctions, which facilitates comparisons between soils.

This methodology is based on standardised soil rooting depths and water retained between suctions of 5 and 1500 kPa (0.05 and 15 bar) for medium and fine textured soils and 10 and 1500 kPa (0.10 and 15 bar) for sandy soils (Hall, Reeve, Thomasson and Wright, 1977). The lower suction limit of 5 to 10 kPa (0.05 to 0.10 bar) approximates to 'field capacity', and the upper limit (1500 kPa) is effectively the 'wilting point'. Thomasson (1995) identifies 5, 6 or 10 kPa as being used for the lower limit of available water (field capacity), but the wider literature reports that there is considerable debate and values between 5 and 33 kPa have been adopted by various workers.

For most soils in the UK, water retained at 5 kPa suction best reflects the water content at field capacity. However, research done by SSLRC in the 1970s shows that the higher suction of 10 kPa more accurately reflects the water retained at 'field capacity' in sandy soils, in which the water table is deeper than 1m. In simple terms, this is because the larger proportion of coarse pores in sandy soils allows water retained at 5 kPa to drain away before equilibrium is reached. In loamy and clayey soils, 'true' equilibrium is rarely reached and water held at 5 kPa leaks out only very slowly.

This methodology of estimating available water from the amounts retained at standard suctions makes rather basic assumptions about plant root behaviour, but has the virtue of defining water reserves unambiguously as a soil property comparable to other properties such as cation exchange capacity, organic matter, or total phosphate content.

The soil depth and suction limits are adjusted for idealised patterns of water abstraction by roots of different crops. Lower suction limits vary from 5 to 10 kPa (0.05 to 0.10 bar), approximating to field capacity, and the upper limit is normally 1500 kPa (15 bar), effectively the wilting point. Thomasson (1995) defines the difference between the

two limits as the total available water (TAW) and introduces the concept of water retention at 200 kPa (2 bar) suction as the upper limit of easily available water (EAW). The EAW, the water held between 5 and 200 kPa (0.05 and 2 bar), is separated from water held at the higher suctions (200-1500 kPa) which is termed restricted available water (RAW). The RAW is much more difficult to abstract, especially from the deeper subsoil. Figure 3 is an attempt to portray the two components of the soil water 'reservoir' available for cereals in relation to soil depth. For a fixed layer of soil, the relationship (for any crop) can be expressed as:

$$TAW = EAW + RAW \quad (11)$$

Adjustments to rooting depths and suction limits for calculating the available water for different crops were first proposed by Thomasson (1979) and these are summarised in Table 4.

In previous research, AWC has been computed as the TAW accumulated to a depth of 100 cm or to a rooting restriction such as rock. However, for MORECS 2.0, AWC varies for different crops, because of their different rooting patterns, and is computed on the basis of the data in Table 4, according to the equation:

$$AWC = EAW + RAW \quad (12)$$

Table 4 shows that, for all crops except potatoes, there is assumed to be a dense rooting pattern in the topsoil or upper soil layer where the TAW between field capacity (5 kPa) and wilting point (1500 kPa) is available to the crop. There is sparser rooting in the subsoil where only the easily available water (EAW) is readily extracted by plants. In the case of potatoes, the rooting pattern permits all the water within the crop rooting depth (70 cm) to be extracted.

The division of the soil water 'reservoir' available to plants into two components is essentially conceptual. In reality, the reservoir is a continuum with water held increasinly 'tightly' as the suction increases. The mechanism of water abstration by roots from the two water reservoirs is essentially the same except that, as the soil dries out and suctions increase, roots have to work much harder to extract the water. These conceptual abstraction models are based on field observations of changes in water content, and/or root density measurements (Russell, 1971). In a recent comprehensive publication, Thomasson (1995) has reviewed the assessment of the soil water reserves available for plants.

Table 4. Adjustment to rooting depths and suctions for particular crops

Crop	Depth (cm)	AWC component	Suction kPa (bar)
Wheat, Barley	0–120	EAW	5–200 (0.05–2)
Oil-seed rape	0–50	RAW	200–1500 (2–15)
Potatoes	0–70	EAW	5–200 (0.05–2)
	0–70	RAW	200–1500 (2–15)
Sugar beet	0–140	EAW	5–200 (0.05–2)
	0–80	RAW	200–1500 (2–15)
Grass	0–100	EAW	5–200 (0.05–2)
	0–70	RAW	200–1500 (2–15)

AWC = available water capacity, EAW = easily available water, RAW = restricted available water

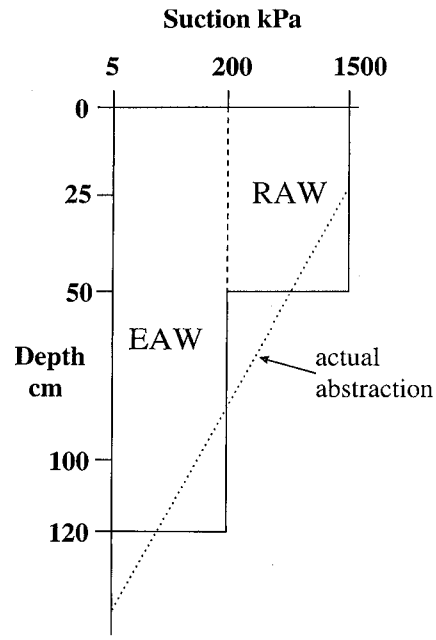

Fig. 3 *Root abstraction model for computing the available water capacity (AWC) for cereals.*

Values of available water capacity (AWC), calculated for the crops in Table 4 and for other types of vegetation, are shown in Table 5 as averages over all the MORECS squares. The ratio EAW/AWC ranges from 50–79%. Jamieson *et al.* (1995) give 65% as the best available estimate of the proportion of easily available to total available water for a soil that has a dense rooting pattern. In MORECS 1.0, EAW/AWC was held at 40% for all crops and soils. Therefore, this new approach adopted for MORECS 2.0 represents a significant improvement in the way the modelling is implemented.

Soil data

The soil available water data that are used in MORECS 2.0 have been extracted from the Land Information System—LandIS. This is a comprehensive information base containing unique soil and related environmental data for England and Wales (Ragg and Proctor, 1983, Hallett, *et al.* 1996, Jones *et al.* 1993). LandIS contains a digital image of the National Soil Map (Soil Survey, 1983) and a National Catalogue of Soils that contains a wide range of

Table 5. Available Water Capacity (AWC) (and the ratio EAW/AWC) for various crops averaged over all the MORECS squares.

Crop	AWC (mm) median	(EAW/AWC (%)) 10% ile	90% ile
Grass	133 (62)	114 (57)	187 (70)
Winter wheat,	134 (71)	114 (66)	192 (79)
Winter & spring barley,	134 (71)	114 (66)	192 (79)
Oil-seed rape	134 (71)	114 (66)	192 (79)
Sugar beet	160 (71)	129 (66)	235 (79)
Potatoes	113 (53)	99 (50)	154 (60)
Orchards	161 (71)	136 (66)	230 (79)
Deciduous trees	305 (71)	262 (66)	429 (79)
Conifers	252 (71)	216 (66)	354 (79)
Upland	67 (62)	57 (57)	94 (70)
Bare soil	36 (40)	31 (40)	50 (40)

The assumption is made that:
1) Upland AWC = 0.5 (grass AWC)
2) Deciduous trees AWC = 2.3 (grass AWC)
3) Conifers AWC = 1.9 (grass AWC)
4) Bare soil AWC = 0.27 (grass AWC)

properties, including water retention and density measurements. All water retention and density data are derived from replicated, undisturbed, volumetric, horizon samples of at least 200 cm^3 (Hall *et al.*, 1977) taken from adequately described benchmark soil profiles, excavated to characterise the nationally recognised soil series. The full range of measurements made on samples taken from these profiles is stored in LandIS.

The spatial National Soil Map data in LandIS has a base resolution of 100 m × 100 m (1 ha) but these data are summarised at 1 km × 1 km and 5 km × 5 km resolution (Jones *et al.*, 1993). The AWC data provided for MORECS 2.0 have been computed at a 1 km resolution for England and Wales. For each crop, the range of AWC and the ratio EAW/AWC in each MORECS square were determined and the median, ten percentile and 90 percentile values computed to replace the low, medium and high AWC in MORECS 1.0.

The AWC values for the different crops have been computed for the 1km squares, such that there are almost 1600 values for each crop in each MORECS square that is wholly on land. The number of values may be substantially less than 1600 for MORECS squares partly in the sea or where no soil (and hence no AWC) has been identified for 1 km × 1 km grid squares. The values are then used to compute the median and percentile AWC for the crop. Frequency distributions of the AWC for grass are shown in Fig. 4 for squares 124 and 151. Square 124 is in Shropshire (the Welsh Borderlands) and has a wide range of soils including some thin soils over rock with small AWC (80–100 mm) and some lowland peats which have very large AWC (>200 mm). By contrast, square 151 is in the south east of England and has less variable soils, mostly clays and heavy loams, and consequently a smaller range of AWC.

Direct measurements of soil water retention and density are not as numerous for Scotland and Northern Ireland as they are for England and Wales. An analogue approach was followed whereby the data from a square in England or Wales, with similar soils and climate, were selected to generate data for Scotland and Northern Ireland.

It is important to emphasise that in developing soil available water data sets for regional or national use, there are no absolutely correct values. It is not possible to measure the actual water contents at field capacity and wilting point in every soil where water balances are required, as this would demand a huge number of highly instrumented sites. Thomasson (1995) describes four 'levels' of operational approach to the estimation of soil available water. In level 1, a standardised soil AWC with an undefined profile depth is used. MORECS 1.0 is an example of this approach. Level 2 uses a standardised soil depth, but also

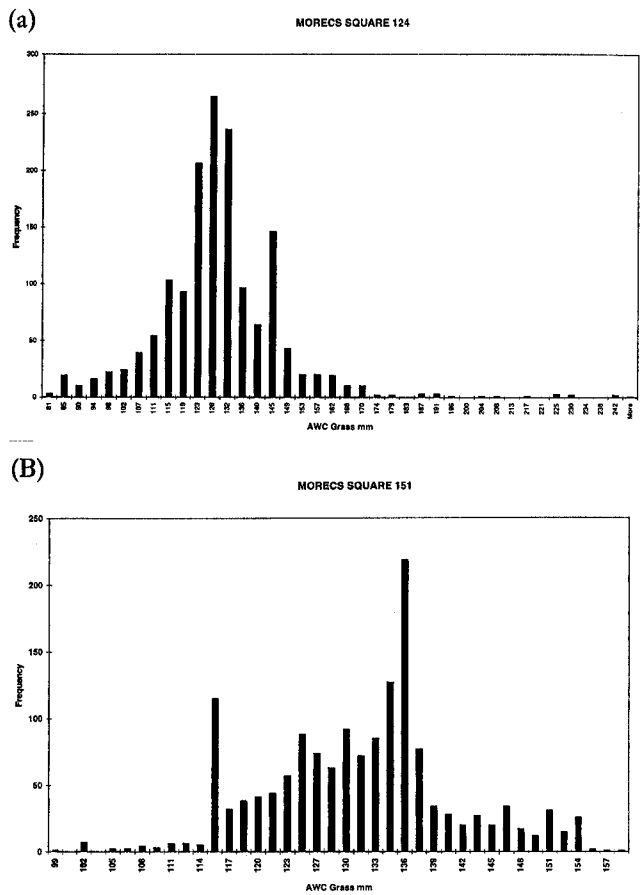

Fig. 4 *Histograms showing the frequency distribution of AWC for grass (mm)*
(a) MORECS square 124 Welsh Borderlands (Shropshire)
(b) MORECS square 151 South east England (Bedfordshire and Hertfordshire).

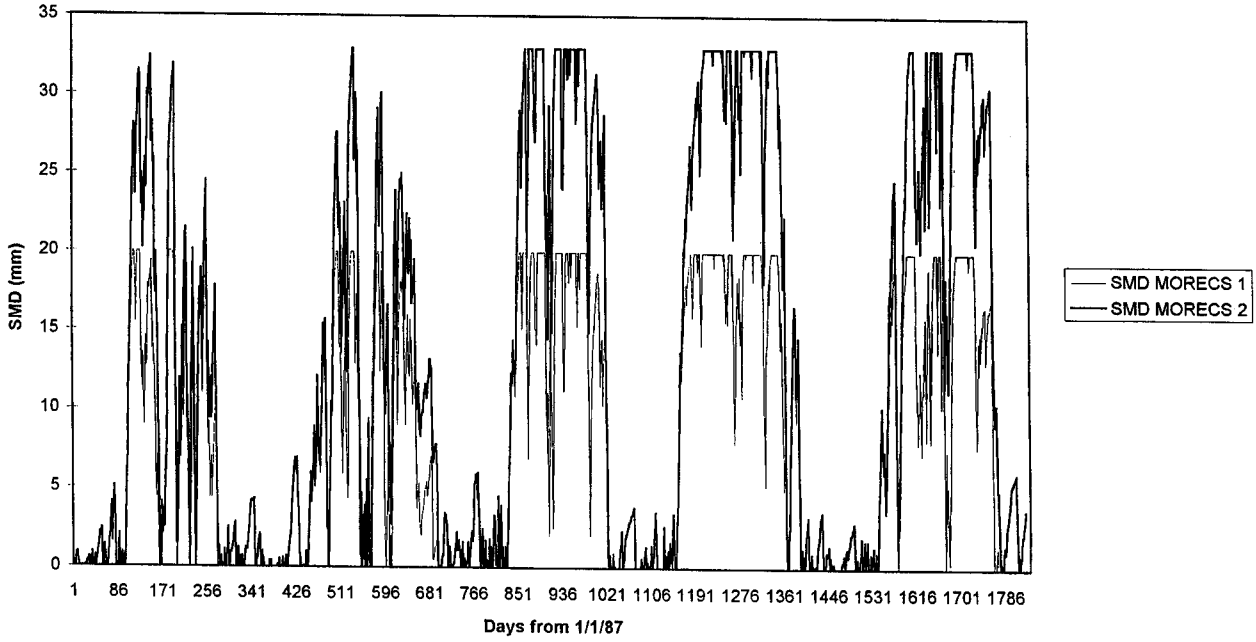

Fig. 5 *A plot of SMD for bare soil at Newport (1987–1991) which compares MORECS 1.0 (medium AWC soil) and MORECS 2.0 (median AWC soil).*

the suction limits between field capacity and wilting point. In level 3 the soil depth and/or suction limits are adjusted for patterns of crop abstraction of water. The full dynamic simulation of water movement in the root zone corresponds to level 4. For MORECS and most other systems requiring soil data for broad scale soil-water modelling, Thomasson's Level 3 is the most realistic approach but it can operate only with simple databases, for example, water contents measured at standard suctions. The dynamic simulation of soil water movement in the root zone (Level 4) is probably impossible. Users of MORECS should recognise this and understand that the soil-water modelling in this new version of the program represents the Thomasson Level 4 approach.

A comparison between MORECS 1.0 and 2.0

A summary of the changes introduced in MORECS 2.0 is as follows:

a) A revised total AWC reflects the actual soils.
b) A revision of the proportion of the soil water which is freely available.
c) Revised leaf area models for winter cereals.
d) Revised canopy resistance for upland.
e) Set-aside and oil-seed rape introduced.

Some of these changes make only slight differences. For example, the effect of the revised leaf area models for the winter cereals can increase the PE in late autumn because of the greater leaf area in MORECS version 2.0. However, the other changes, especially to the soils information, can lead to more significant changes. For example, MORECS 1.0 had the AWC for grass and medium soil as 125 mm in all squares. In version 2.0, the AWC for grass and median soil can vary from 106 mm (square 148) to over 200 mm (square 65). Examples of some of the differences between versions 1.0 and 2.0 for bare soil, winter wheat and upland are given in Fig. 5 for square 114. The single site version of the model was used with 5 years of weather data from the site at Newport in Shropshire. The years between 1987 and 1991 were chosen to show the effects of cool, wet summers (1987, 1988) and warm, dry weather (1989–1991). Some results for oil-seed rape are shown in Fig. 6 to contrast the effects of warm and cool seasons.

BARE SOIL

Figure 5 compares the SMD for medium (version 1.0) and median (version 2.0) AWC soil. The different AWC values are the cause of the differences here: MORECS 1.0 has a value of 20 mm, while MORECS 2.0 recognises that the median soil in square 114 has an AWC of 33 mm. Hence, in dry summer weather, MORECS 2.0 reaches larger SMD values. The version 2.0 has fewer days with a positive EP value and, over the 5 year period, there was 107 mm more EP for version 1.0 (1257 mm compared to 1150 mm).

WINTER WHEAT

Figure 6 shows the SMD results for the high (version 1.0) and the 90 percentile (version 2.0) AWC soil. The 90 percentile soil in square 114 has an AWC of 134 mm for winter wheat while version 1.0 sets its high AWC value at

175 mm. In this case, the SMD for MORECS 1.0 can reach higher values than version 2.0 in dry summers. However, at more moderate SMDs between about 75 and 110 mm, MORECS 2.0's SMDs are higher because version 2.0 has evaporation at the potential rate (greater proportion of soil water freely available) whereas in version 1.0 AE is less than PE.

UPLAND

The upland results in Fig. 7 compare the PE values in summer. They show the higher PE for version 2.0 due to the lower canopy resistance value.

OIL-SEED RAPE

Fig. 8 compares a cool growing season (1986-1987) and a very warm season (1989–1990). The cooler year was associated with a slow accumulation of thermal time and, in winter and spring, there was very little accumulation until day 105. As a result, leaf growth was calculated to be slow with low PE. In the warm year, crop growth and development was much faster.

Conclusion

In the revised version of MORECS, the basic science is largely unchanged but improvements have been made to the treatment of soils information, to the estimates of land use and to the crop models. MORECS 2.0 should provide better estimates of evaporation, soil moisture and effective precipitation than MORECS 1.0 and marks a major step forward in modelling crop water balances for improved operational land management.

Acknowledgements

Thanks are due to many people who helped formulate ideas, but particularly to J. Ashcroft for deriving the land uses for each square from the original data sets, and to K. Adamson who painstakingly traced woodland areas from maps. J. Finch provided satellite land cover data, Mary Proctor computed the AWC data, and R. Harding and R. Ragab provided help in many other ways.

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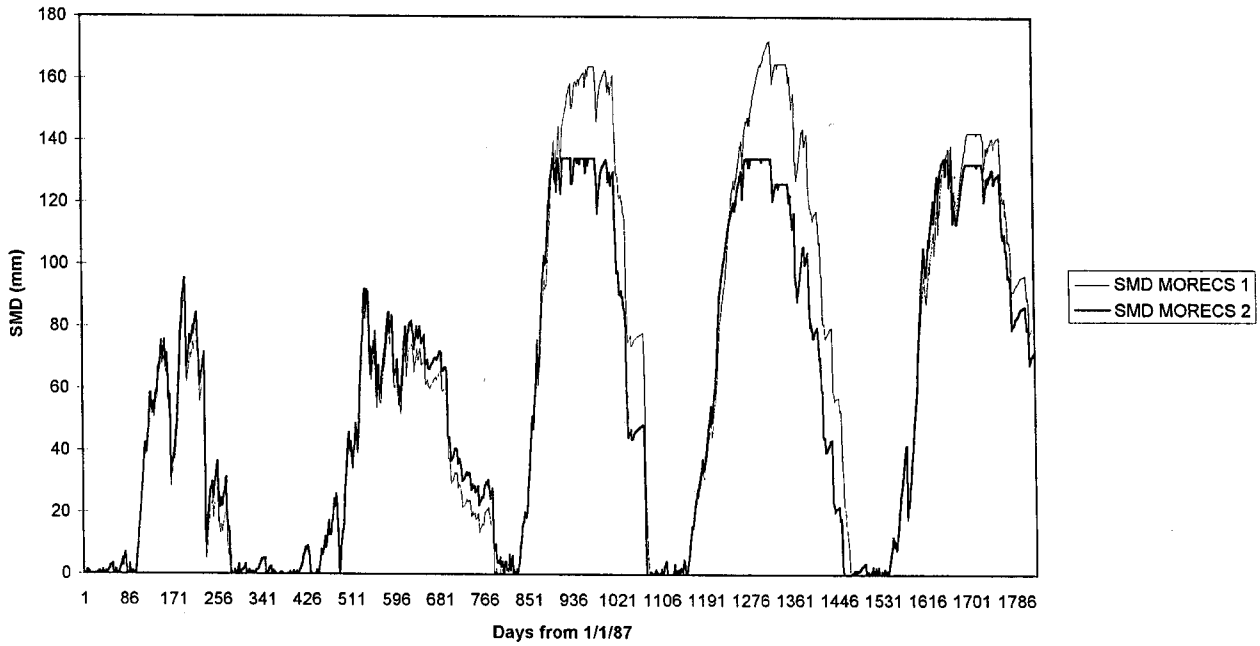

Fig. 6 *A plot of SMD for winter wheat at Newport (1987–1991) which compares MORECS 1.0 (high AWC soil) and MORECS 2.0 (90 percentile soil).*

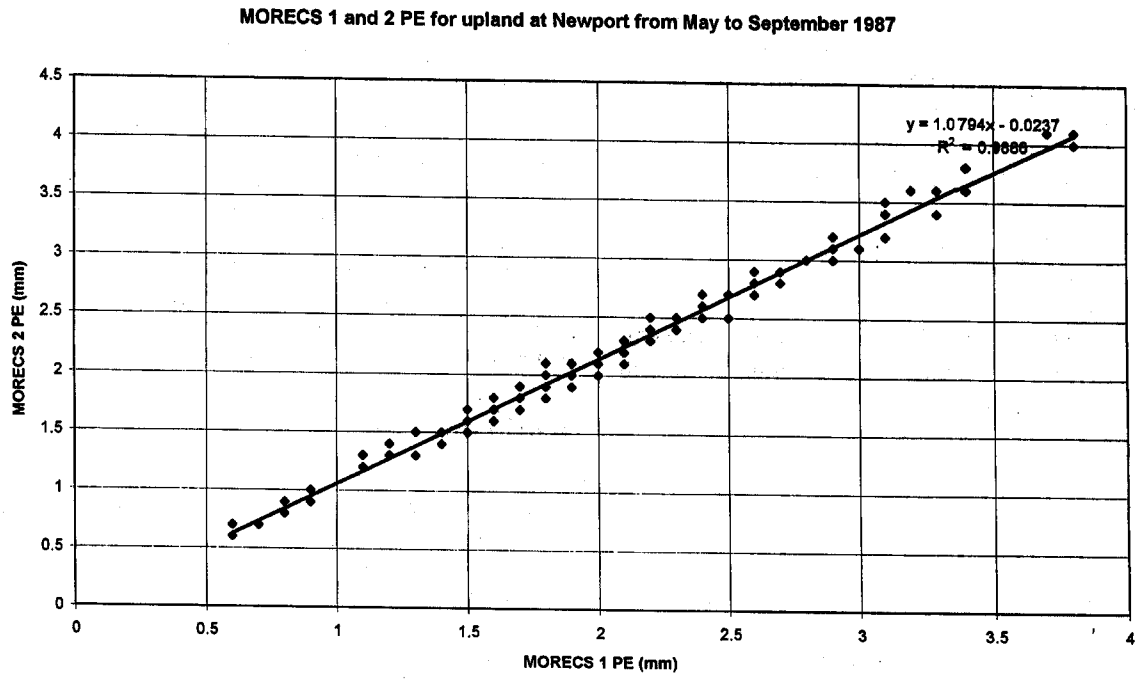

Fig. 7 *A plot of daily PE (MORECS 2.0 against MORECS 1.0 values) for upland at Newport from May to September 1987.*

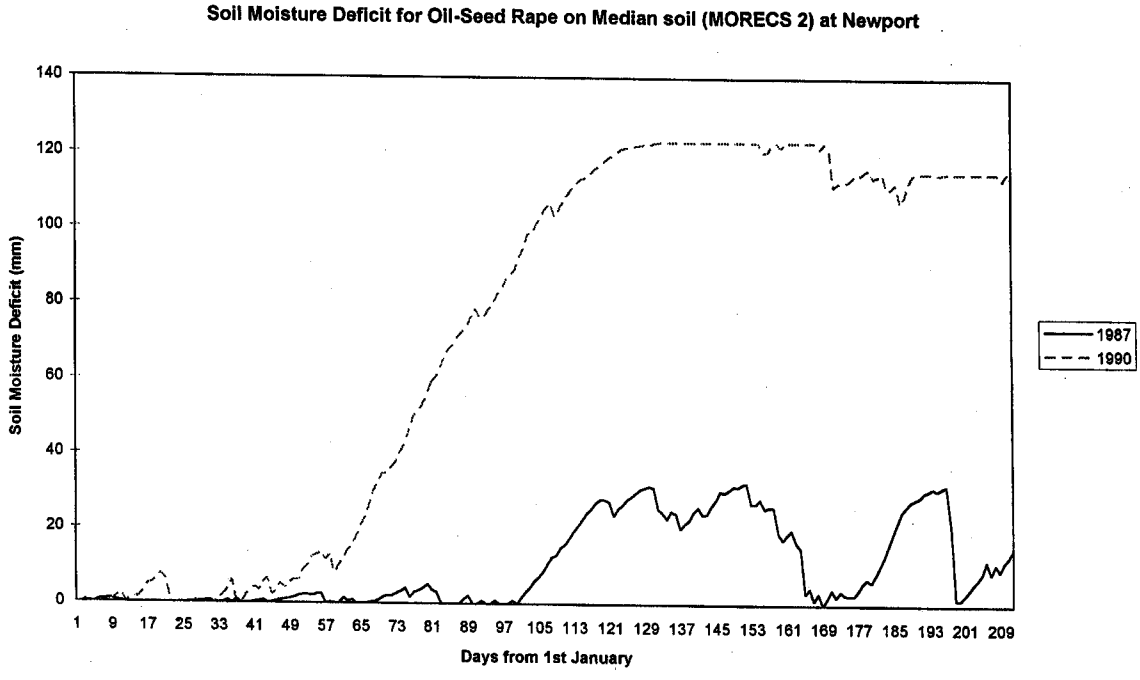

Fig. 8 *MORECS 2.0 values of SMD for oil-seed rape in 1987 (cool growing season) and 1990 (warm growing season).*

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