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Scale impacts on spatial variability in reference evapotranspiration

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Abstract

Evapotranspiration (ET) is one of the most important components in the hydrological cycle, and a key variable in hydrological modelling and water resources management. However, understanding the impacts of spatial variability in ET and the appropriate scale at which ET data should be incorporated into hydrological models, particularly at the regional scale, is often overlooked. This is in contrast to dealing with the spatial variability in rainfall data where existing guidance is widely available. This paper assesses the impacts of scale on the estimation of reference ET (ETo) by comparing data from individual weather stations against values derived from three national datasets, at varying resolutions. These include the UK Climate Impacts Programme 50 km climatology (UKCP$_{50}$), the UK Meteorological Office 5 km climatology (UKMO$_{5}$) and the regional values published in the Agricultural Climate of England and Wales (ACEW) (Smith, 1976). The national datasets were compared against the individual weather station data and the UKMO$_{5}$ was shown to provide the best estimate of ETo at a given site. The potential impacts on catchment modelling were then considered by mapping variance in ETo to show how geographical location and catchment size can have a major impact, with small lowland catchments having much higher variance than those with much larger areas or in the uplands. Some important implications for catchment hydrological modelling are highlighted.

Keywords: catchment; England and Wales; Penman-Monteith; regionalisation; water resources.

1 Introduction

Evapotranspiration (ET) is the loss of water to the atmosphere via by the combined processes of evaporation (from soil and plant surfaces) and transpiration (from plant tissues). It constitutes an essential component in almost all hydrological water balance studies, whether modelling the impacts of climate change on local river flooding (Booij, 2005), studying changes in land use at a catchment scale (Holman et al., 2005) or predicting regional agricultural irrigation demand (Rodriguez-Diaz et al., 2007). Although ET does not vary as much as rainfall over short distances, taking into account its spatial variability can be important, particularly if assessments are concerned with analysing extreme regional phenomena such as droughts or desertification at the river basin scale (Dalezios et al., 2002). Catchment ET is a function of the weather, land cover and wetness and measurement of actual ET is difficult. Therefore, in many modelling studies, ET is estimated from a reference which is a function of the weather and reflects the potential of the atmosphere to evaporate water. This is modified for the particular surfaces under consideration by the use of an appropriate crop coefficient (Pereira et al., 2015). Potential evaporation (PE: Penman, 1948), potential transpiration (PT: MAFF, 1967) or potential evapotranspiration of a hypothetical surface (ETo, Allen et al., 1994a) have been used as the reference, among others (Pereira et al., 1999).

In many instances, the lack of spatially distributed ET data imposes a real limitation on hydrological assessment, particularly when other datasets such as rainfall, land use and soils are often available at high spatial resolutions. Even where meteorological data are available to generate ET maps, their spatial accuracy will depend on the number of individual stations used, their density across the study area and the interpolation methods employed (Foyster, 1973). Some water balance studies (e.g. Hess, et al., 2015) have applied ET estimation models to small homogeneous units and then applied a weighted average to compute a regional based ET estimate. Others have relied on remote sensing (satellite imagery) and surface meteorological data to estimate ET, using for example, SEBAL (Surface Energy Balance Algorithm for Land) (Bastiaanssen *et al.*, 2005).

The most common approach to addressing spatial variability in ETo seems to be selecting a 'representative' site with long-term historical meteorological data and then using this to generate a dataset for input into a water balance model. The fundamental question is how representative is the site to the larger study area, and what uncertainty does this geospatial simplification introduce in hydrological modelling?

Despite the importance of reference ET in hydrological modelling there is surprisingly limited research in the literature on assessing its spatial variability. For selected countries in Europe, Gurnell (1981) produced isopleth maps of seasonal potential evapotranspiration (PET: Penman, 1962) using a network of 70 weather stations and interpolating PET estimates using polynomial trend surface analysis. Robbins-Church *et al* (1995) produced a series of regional-scale ET maps for the northeast United States in support of water resource studies investigating runoff and acidic deposition, and in Spain, Rey (1999) produced maps of ETo based on the Penman-Monteith formula derived from a network of 920 thermopluviometric stations for use in climate change impact studies on vegetation. Over the last decade, there has also been major research progress in the application of remote sensing for deriving near real time spatially distributed estimates of ET at regional and global scales (Mueller et al., 2013). For example, the MOD16 1 km^2 ET dataset covering the period 2000-2010 is now available at 8-day, monthly and annual intervals Mu et al. (2011). More recently, Cammalleri *et al* (2014) developed a remote sensing data fusion methodology to map daily ET at the field-scale over rainfed and irrigated agricultural areas using Landsat and MODIS data.

With competition for limited water resources and particularly given concerns regarding the impacts of global changes in temperature and radiation (two important factors influencing ETo), hydrological assessments need to recognise more explicitly the spatial variability in

ETo and its consequent impacts on water supply-demand balances. Over the last decade, hydrological studies have benefitted significantly from the increased capability and functionality of geographical information systems (GIS) enabling georeferenced databases to be to integrated and spatially modelled. It is therefore surprising that many national and international gridded climate datasets rarely include information on reference ET instead preferring to leave estimation to the end user, recognising that there are many different estimation methods.

2 Approach

Smith (1976) divided England and Wales into 52 agroclimatic regions, some of which were further sub-divided, giving 71 discrete agroclimatic areas (Figure 1). The regions were based on identifying areas with the greatest degree of uniformity in farming type, assuming that the farming types within a particular region were a reflection of local climate and soil conditions. This dataset is known as the Agricultural Climate of England and Wales (ACEW) and was produced to provide growers, agricultural consultants, land resource planners and researchers with a summary of important areal values for a range of key agrometeorological parameters (Smith, 1976). The dataset contains a range of data based on direct measurements (e.g. mean air temperature, rainfall and hours of sunshine), derived values (e.g. potential transpiration, radiation) and agro-meteorological factors (e.g. length of growing season, soil moisture deficit, date of return to field capacity). Although this climate atlas has been in circulation for in excess of 40 years, many still rely on it as an alternate source of free (albeit non-digital) data on the spatial variability of agroclimate for England and Wales. ACEW reported mean monthly estimates for potential transpiration from a green crop (PT, Smith, 1976) which is broadly analogous to ETo. PT was calculated for the period 1941-71 using the Penman method (MAFF, 1967) for a large network of meteorological stations. PT isopleths were drawn and the average monthly PT calculated for each agroclimatic region. The monthly values quoted were "thought to be reliable within ±2 mm" (Smith, 1976 p10) and were designed for use at the "macro or possibly, meso-scale" (Smith, 1976 p12).

The UK Climate Impacts Programme (UKCIP) is responsible for providing a range of users with climate data in support of climate change impact assessment. Since 1998, the UKCIP has managed a climatology database containing both baseline (long-term average) and future climate data (Hulme *et al*., 2002; Jenkins *et al*., 2009) for 50 km × 50 km grid squares (Figure 1). The datasets contain long-term average (LTA) historical monthly data corresponding to 1961-1990 for a range of climate variables, including those required to calculate ETo.

The UKCIP climatology also includes a higher resolution (5 km × 5 km) dataset based on observed data produced by the UK Meteorological Office (UKMO) (Figure 1). This dataset contains data for 36 monthly climate variables, for the period 1961-2011, of which 24 are available free for research purposes via the UKCIP (Perry and Hollis, 2004) including those required to calculate ETo.

Many methods have been developed to estimate PE or ETo relying on the integration of meteorological parameters. The methods range from simple use of evaporation pan data multiplied by a coefficient (Grismer *et al*., 2002) to the use of empirical relationships (e.g. Linacre, 1977) or more complex approximations of the physical processes involved based on either temperature (e.g. Thornthwaite, 1948; Hargreaves and Samani 1982) or radiation (e.g. Makkink, 1957; Priestley and Taylor, 1972; Turc, 1961). Substantial research effort has been directed towards the development of combination methods, such as Penman (1948), subsequently modified by Monteith (1965). A detailed review of ETo methods and their accuracy is given in Allen *et al* (1994a). Following an extensive comparative assessment of estimation methods, the FAO Penman-Monteith equation has been adopted as the standard in both humid and arid environments by the International Commission on Irrigation and Drainage (Allen *et al*., 1994b); the Food and Agriculture Organisation of the United Nations

(Allen *et al.*, 1998); and the American Society of Civil Engineers (Allen *et al.*, 2005). ETo is estimated from mean air temperature, net radiation, soil heat flux, mean wind speed and mean vapour pressure deficit (Equation 1) (Allen *et al.*, 1998):

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad [1]$$

Where,

ETo is reference evapotranspiration (mm d^{-1}); R_n is net radiation at the crop surface (MJ m^{-2} d^{-1}); G is soil heat flux density (MJ m^{-2} d^{-1}); T is mean daily air temperature at 2 m height (°C); u_2 is wind speed at 2 m height (m s^{-1}); e_s is saturation vapour pressure (kPa); e_a is actual vapour pressure (kPa); Δ is the slope of the vapour pressure curve (kPa $°C^{-1}$), and; γ is the psychrometric constant (kPa $°C^{-1}$). When not available, solar radiation can be estimated from sunshine hours and soil heat flux can be estimated from change in daily mean air temperature (Allen *et al.*, 1998).

The ACEW and UKCIP data sets allow estimates of potential or reference evapotranspiration at a regional level (agroclimatic regions or grid squares respectively). However, these are based on different data periods and regionalisations. This aims of this paper are therefore threefold; (i) to compare PT and ETo estimated from ACEW and UKCIP respectively against contemporary (1981 – 2010) estimates of ETo from individual weather station sites; (ii) to compare ETo derived from the UKMO 5 × 5 km gridded data against contemporary (1981 – 2010) estimates of ETo from individual weather station sites to assess whether this could be used to generate regionalised estimates of monthly average ETo; and (iii) to assess how spatially-derived uncertainty in ETo estimates might then impact on catchment scale studies. The analysis is undertaken for England and Wales but is relevant to other areas where appropriate datasets are available.

The study comprised four sequential stages:

1. Three spatially distributed datasets of average monthly ETo were generated; one from a published source and two based on gridded datasets of climate variables at 50 × 50 km and 5 × 5 km scales, respectively.
2. Each was compared with average monthly ETo from long-term historical (observed) weather data from a network of weather stations to determine how well the spatially averaged ETo data compared to estimates from individual weather stations.
3. The 5 × 5 km dataset was then used to map the spatial variability in ETo across England and Wales.
4. Three regionalisations of ETo - based on agroclimatic areas, hydrological catchments and an arbitrary grid - were compared in order to identify the most useful regionalisation for summarising spatial variation in ETo.

As each stage depended on the outputs of the previous stage, the methods and results for each stage are presented together. Finally, the relevance and importance of factoring in spatial variation in ETo to hydrological modelling was considered.

3 Spatially distributed datasets of average monthly ETo

Data on temperature, solar radiation, wind speed and humidity were extracted from the 50 km × 50 km UKCIP data (Hulme *et al*., 2002; Jenkins *et al*., 2009) and mean monthly ETo for each grid pixel was calculated using the method of Penman-Monteith (equation 1). These data are referred to as UKCP_{50} ETo.

The UKMO national 5 × 5 km gridded dataset was derived from a historical database containing observations of weather elements from an irregularly spaced network of meteorological stations across the UK (Perry and Hollis, 2004). The density of the station network varied from an average of one station per 3,481 km^2 for pressure, cloud and wind (70 stations), to 441 km^2 for maximum and minimum temperature (540 stations), to 49 km^2 for rainfall (4400 stations) (Perry and Hollis, 2004). There was also considerable spatial variation, with sparse data coverage in some regions, most notably in upland areas. However, rigorous quality control procedures were applied to the daily observations by the UKMO, including substitution of poor quality data, filling in missing data, and applying range and consistency checks prior to creating the final gridded database. A detailed description of the procedures used to produce a regular grid of values from the irregularly spaced station (point) data and the climate interpolation (using inverse distance weighting and accounting for altitude, terrain, distance from the coast and urbanisation) to generate the final gridded climate dataset is given in Perry and Hollis (2004). Maximum and minimum air temperature, mean relative humidity, sunshine duration and mean wind speed were extracted for each grid pixel and monthly ETo was calculated for each year (1981 – 2010). The average of the 30 years ETo for each month is referred to as $UKMO_5$ ETo.

4 Performance of spatially distributed ETo

4.1.1 Individual weather stations (site)

Fifteen weather stations were selected (Table 1) on the basis of having long-term (corresponding to 1981 – 2010) average climate data available and reflecting the range of agroclimatic conditions that exist across England and Wales. For each station and month, long-term average ETo was calculated using the method described in Allen *et al.* (1998) from long-term average maximum and minimum air temperature, sunshine duration and wind speed given by the UK Met Office. Hourly records of dewpoint temperature or wet and dry bulb temperatures were used to estimate long-term average (1981 – 2010) monthly vapour pressure (Met Office, 2006). These estimates are referred to as ETo_{site} and range from 539 mm year^{-1} at Durham to 676 mm year^{-1} at Bedford (Table 2).

4.1.2 Statistical comparison between individual site and national datasets

The individual weather station (ETo_{site}) data were used as reference values against which each national ETo dataset (ACEW, $UKCP_{50}$ and $UKMO_5$) was compared using two difference-based statistical indicators; the root mean squared error (RMSE) and mean bias error (MBE) (Jacovides and Kontoyiannis, 1995). The RMSE allows a comparison of the actual differences between the ETo_{site} values and those estimated using the two gridded datasets ($UKCP_{50}$ and $UKMO_5$) and the ACEW atlas. The smaller the RMSE value, the better the agreement between the methods; however, the RMSE does not differentiate between under and over-estimation of ETo. The mean bias error (MBE) provides information on dataset accuracy, with a positive value giving the average amount of over-estimation in ETo and vice versa. The smaller the absolute value, the better the agreement between the two datasets. For each paired set of values, the RMSE and MBE were calculated for the winter (December to February), spring (March to May), summer (June to August) and autumn (September to November) periods, and then annually. As average ETo_{site} is considerably higher in summer than winter, these were also expressed as a percentage of the long-term average ETo_{site} to allow comparision of the performance of the alternative data set across seasons.

4.1.3 Results

A comparison between the mean monthly ETo for each weather station (ETo_{site}) and the three national datasets (ACEW, $UKCIP_{50}$, and $UKMO_5$), by month, is given in Figure 2 to Figure 4. The RMSE and MBE statistics (Table 3) show that ACEW underestimates ETo_{site}, particularly at low values of ETo between August and March. This is partly due to the different time periods used, but the use of PT as a reference in ACEW accounted for an underestimate of 6% in annual ET (see Figure 5 which compares the two ET estimation methods with the same climate data). The $UKCP_{50}$ and $UKMO_5$ values show a much closer correlation with ETo_{site}. Overall the $UKMO_5$ based estimates for ETo fit more closely to the ETo_{site} than either the $UKCP_{50}$ based estimates or the ACEW, with an MBE of zero, although this results from an over-estimate in winter (MBE = 3.4 mm/month) and under-estimate in summer (MBE = -3.6 mm/month).

5 Spatial variation in ETo

Given the temperate maritime climate and diverse topography of England and Wales, ETo can vary quite substantially over relatively short distances; it is therefore important to account for any spatial differences in ETo in hydrological modelling studies. Figure 6 shows the spatial distribution of ETo based on the most accurate, and highest resolution of the three methods considered above. Maps have been produced to highlight the spatial ETo differences for three periods, (i) the month in which peak ETo rates generally occur (July), (ii) the summer period (April to September) and (iii) annually.

For July, the highest ETo values (>100 mm) are recorded in eastern and south eastern England, with pockets in London and along the south coast (where sunshine and radiation are strongest). The lowland, inland regions show the greatest uniformity in ETo. The lowest ETo values (<50 mm) are recorded in the upland regions notably in parts of Wales, the south west and northern England. The summer and annual maps show a similar pattern but highlight particular regions (e.g. West Midlands, parts of Lincolnshire, Kent) where seasonal ETo values are much higher. The maps in Figure 6 should alert hydrologists and others modelling at the catchment scale of the need to consider carefully the implications of spatial and temporal ETo variability in their analyses.

6 Regionalisation of ETo

In practice, the choice of ETo data used for hydrological modelling is often governed by a number of factors including the scale of enquiry, having access to high quality low cost historical daily climate data, and the modellers’ perception or knowledge of the extent to which spatial variations in topography and land use might influence evapotranspiration rates. The ETo maps (Figure 6) show how ETo varies spatially in England and Wales, however, one important question that arises is the extent to which these spatial variabilities in ETo are important at a range of scales.

Three regionalisations of England and Wales were compared (Table 4); the UKCP 50 km boundaries; the ACEW agroclimatic regions (Smith, 1976); and the hydrological areas defined by the Environment Agency (EA) as part of its catchment abstraction management (CAMS) process (EA, 2010) (Figure 7). As the $UKMO_5$ dataset was shown to be the most representative (based on the comparison with ETo_{site} above), it was used as the basis for comparison. In order to compare the variation due to the regionalisation partitioning, two methods were used: Variance component analysis and the Brown–Forsythe test (Brown and Forsythe, 1974).

Variance component analysis was first used to compare the within-region variation under each regionalisation. Using ANOVA, the variation of each regionalisation method comprises two sources: (i) between regions variation is the variation due to difference between regions means (denoted by $SS_{BR}^{(k)}$) and indicates the proportion of the total variation that is explained by the differences among regions (Casella, 2008) and (ii) the remaining variation is due to the within region variation which also shows the residual variation, or variation of each observation around each region's mean. The within regions variation can be compared using a pair-wise F-test based on the residual variance.

Table 5 summarises the variation analyses for the three regionalisation methods using the variance component method. For January the UKCP 50 km regionalisation has the largest contribution in the total variance (74%) which is significantly ($p < 0.001$) different to both the EA CAMS and ACEW regionalisation methods which have the same contribution in the total variance (54%). In July the UKCP 50 km regionalisation has the largest contribution in the total variance (90%) and the CAMS regionalisation method has the lowest effect contribution (86%). These suggest that the UKCP 50 km regionalisation is capturing the spatial variability in ETo better than the other two methods.

The Brown–Forsythe method can be also used to assess differences in group variance among the regionalisations. This method is more robust with respect to outliers and is ideal when the distributions of data deviate even slightly from normality. In order to compare the performance of the three regionalisations, the UKMO$_5$ data for January and July were expressed as absolute deviations from the median for each region;

$$d_{ij} = | ETo_{ijk} - \tilde{ETo}_{.jk} |$$

Where ETo_{ijk} is the UKMO$_5$ estimate of ETo for the i^{th} value in region j using regionalisation method k, and $\tilde{ETo}_{.jk}$ is the median of the *i* values of ETo in region *j* for a given month. The mean absolute deviation from the median (MAD) was calculated for each region in order to compare the spatial variation of ETo among regions within a regionalisation, and an analysis of variance of the transformed data used to compare the overall performance of the three regionalisations.

Table 5 shows the MAD for the three regionalisations and two months. A pair-wise comparison of the mean absolute deviation between the regionalisation methods confirmed that the ACEW and CAMS regions are not significantly different from each other (p=0.31) in January whereas in July, all three regionalisations are significantly different from each other, reinforcing the conclusion of the variance component analysis. This suggests that the UKCP$_{50}$ grid provides less within-region variation in ETo than the other two regionalisations.

7 Implications for hydrological modelling

Figure 7 shows the MAD for each region within England and Wales according to the three regionalisations.. Where MAD is low, the regional average ETo could be used with low uncertainty, however, where it is high, spatial variability in ETo introduces larger uncertainty and hydrological modelling needs to consider the spatial variability in ETo more explicitly.

In January, as the mean values of ETo are small, the MAD is also small, being <2 mm/month for all regions and regionalisations with the exception of parts of north east England under the ACEW and CAMS regionalisations. In the month of maximum ETo (July) the MAD is generally low in eastern, central and southern England (all lowland areas) in all three regionalisations, with the notable exception of the UPCP 50 km grid square around London. The differing performance of the regionalisations is not simply a function of the size of the regions. The CAMS regionalisation has the smallest mean region size of the three approaches regionalisations, yet is least successful in capturing the within region variation. This may be because, by definition, a hydrological catchment encompasses a range of topography from headwaters to catchment outlet. Similarly, there is no overall correlation between CAMS size and MAD. For example, although the Wye in south Wales is the largest (4,178 km^2) and has the third highest July MAD (5.4 mm/month), the Cam and Ely Ouse (3,664 km^2) in eastern England is the second largest CAMS area and has one of the lowest values of MAD in July (0.9 mm/month).

The MAD values for ETo by CAMS areas are of particular relevance to hydrologists. This map (Figure 7) identifies specific areas where both low and high MAD in July ETo occur, and can be used in support of defining the ETo data requirements for hydrological studies. For example, a number of small, lowland, inland CAMS areas have a low July MAD (< 1 mm/month). Studies in these CAMS areas could justifiably rely on using the catchment average value of ETo. In contrast, a number of CAMS areas in northern England and Wales all have high values of July MAD (> 4 mm/month). Many of these CAMS areas are in upland areas and of varying size and studies should therefore carefully consider the spatial variability in ETo within these areas in a more spatially explicit way. Readers interested in the geographical distribution of CAMS catchments in England and Wales are referred to EA (2010).

8 Conclusions

The comparison of the ACEW ETo regional estimates of PT and ET_{site} has shown that the published regional values (Smith, 1976) are no longer fit for purpose. The use of PE is known to underestimate ET due to insufficient consideration of the effect of wind speed (Thom and Oliver, 1977) and this study has shown an underestimate of long-term average ET of 20%. However, the 5 km resolution gridded data (Perry and Hollis, 2004) can be used to replicate ETo at a point. The analysis of the regionalisations has shown that, perhaps surprisingly, the agroclimatic regions of Smith (1976) are not the best way to summarise ETo in England and Wales, rather an arbitrary 50 km grid provides less within-region variation and therefore better accounts for the spatial variability of ETo.

There are hidden problems associated with either ignoring such variability or estimating ETo using limited only climate data, which are of particular relevance to climate change impacts research, and those concerned with assessments of hydrology on future water resources. For these types of studies it is important to not only choose an appropriate method that provides the most accurate estimate of ETo, within the constraints of data availability, but also avoids introducing additional uncertainty into the subsequent hydrological modelling and analysis. Failure to consider these issues at the outset may result in error propagation through the methodology; with impact assessments reflecting errors in ETo estimation, rather than climate change *per se*.

Using England and Wales as a case study, this paper quantifies and maps the impacts of scale on ETo estimation by comparing data from a network of weather stations with long-term historical data against equivalent values derived from three publically available datasets, all at varying resolutions. These datasets have been widely used by scientists and others involved in catchment-scale studies, most recently in climate impact assessments. However, in the absence of alternative guidance, most have generally ignored the potential impacts that any spatial ETo variability might have on their modelling approaches and simply assumed single site data to be representative for large areal based water balance or climate impact assessments. This study provides new valuable insight and information for the hydrological research community to help understand the importance of spatial ETo variability and guide the appropriate selection of ETo datasets for input into regional-scale modelling.

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Derived reference evapotranspiration values are available on request from the authors at t.hess@cranfield.ac.uk

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Appendix I: Definitions of evapotranspiration terms.

Term	Abbreviation used	Definition
Evapotranspiration	ET	The measured (or estimated / modelled) sum of evaporation and transpiration from a particular surface at the soil water content and agronomic condition at the time of measurement.
Potential evaporation	PE	Evaporation under conditions of full water availability and saturation at the surface so that vapour pressure deficit at the surface and surface resistance become null. It is analogous to Penman's open water evaporation (Penman, 1948), thus it only applies to a crop after the crop surface has been wetted by rain or sprinkling.
Potential transpiration	PT	Potential evapotranspiration (Penman, 1962) or potential transpiration (MAFF, 1967) from an extensive surface of grass under stress-free conditions. The two terms are broadly synonymous. However, as a "grass" surface may vary in terms of height, albedo and canopy resistance, PET and PT are potentially ambiguous terms.
Potential evapotranspiration	PET	
Reference evapotranspiration	ETo	The evapotranspiration rate from a (defined) extensive reference surface, not short of water. Several reference

		surfaces have been defined, but Allen et al. (1994) defined reference ET as‘the rate of evapotranspiration from a hypothetical crop with an assumed height of 12 cm, a fixed canopy resistance of 70 s m^{-1}, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water’.

Table 1 Meteorological summary for the weather stations used in this study.

Station	**Lat°N**	**Long°E**	**Alt (m)**	**Agroclimatic area**	**Annual rainfall, 1981-2010 (mm)**
Aberporth	52.139	-4.571	133	50	887.7
Bedford	52.134	-0.461	24	28	597.7
Blackpool	53.821	-3.054	12	9	882.7
Boscombe Down	51.161	-1.754	126	36	748.6
Boulmer	55.421	-1.600	23	1S	689.3
Durham	54.775	-1.583	70	5	651.1
Lyneham	51.503	-1.992	145	30	745.3
Manchester Airport	53.358	-2.267	74	14	867.1
Marham	52.651	0.569	21	24	652.6
Shawbury	52.794	-2.663	72	18N	659.9
St Mawgan	50.441	-5.003	95	40	1017.4
Valley	53.252	-4.537	10	47	841.1
Waddington	53.175	-0.521	68	17W	614.4
Wattisham	52.123	0.961	89	29	613.8
Yeovilton	51.006	-2.640	20	35	708.5

Table 2 Mean monthly ETo (mm month^{-1}) for each weather station.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Aberporth	21.0	23.9	38.8	58.2	81.1	87.1	91.6	80.9	58.6	39.4	23.7	20.3	624.5
Bedford	13.5	19.9	42.3	65.1	87.8	98.7	115.1	104.4	67.7	36.9	15.7	9.3	676.4
Blackpool	16.0	25.5	36.6	61.7	88.7	94.7	100.0	88.8	60.5	35.7	22.0	12.2	642.5
Boscombe Down	11.8	17.4	39.1	61.7	87.7	100.0	112.2	97.7	61.8	31.6	13.0	8.7	642.8
Boulmer	20.4	24.8	41.1	53.5	72.9	83.5	89.9	77.7	53.7	33.2	19.4	17.0	587.1
Durham	12.6	18.8	37.6	53.4	76.3	82.3	91.2	76.9	48.2	23.0	10.3	8.8	539.4
Lyneham	12.8	20.0	41.1	65.2	90.7	103.7	113.8	98.1	64.0	33.5	14.5	10.0	667.5
Manchester Airport	13.3	20.2	39.1	59.5	88.1	93.1	100.8	85.5	56.2	33.0	12.0	6.8	607.5
Marham	12.6	19.4	40.9	64.7	91.8	99.6	114.2	100.3	63.9	34.8	13.7	9.2	665.1
Shawbury	13.9	19.6	39.4	61.4	86.2	96.8	106.7	89.9	59.4	31.4	14.8	9.9	629.2
St Mawgan	17.9	23.3	40.3	62.6	83.8	91.9	97.8	86.6	61.6	40.1	23.8	16.1	646.0
Valley	22.4	24.5	39.7	59.5	85.9	91.4	96.3	83.9	61.1	41.7	26.5	19.6	652.7
Waddington	14.4	21.3	42.3	64.4	90.9	99.6	114.0	100.2	64.7	35.2	15.0	10.7	672.6
Wattisham	12.9	18.8	40.0	64.4	90.5	101.1	116.0	103.6	66.0	34.7	13.7	9.6	671.3
Yeovilton	14.2	19.8	41.2	63.1	88.7	100.7	109.8	95.2	62.3	33.9	15.3	10.5	654.9

Table 3 RSME and MBE (mm month^{-1} and % of LTA ETo_{site}) for comparisons between the weather station (ETo_{site}) data and the three alternative datasets ($UKMO_5$, $UKCP_{50}$ and ACEW), by season.

Season[†]	**ACEW**		**$UKCP_{50}$ grid pixel**		**$UKMO_5$ grid pixel**	
	RMSE	MBE	RMSE	MBE	RMSE	MBE
Winter	11.8	-11.4	4.5	0.8	3.8	3.4
	73%	-71%	28%	5%	24%	21%
Spring	7.1	-6.6	10.8	-8.8	3.3	-1.8
	11%	-11%	17%	-14%	5%	-3%
Summer	14.4	-11.9	11.9	-8.1	4.4	-3.6
	15%	-12%	12%	-8%	5%	-4%
Autumn	13.4	-12.9	7.1	-1.3	3.3	1.8
	36%	-34%	19%	-3%	9%	5%
Year	12.0	-10.7	9.1	-4.3	3.7	0.0
	23%	-20%	17%	-8%	7%	0%

[†] Winter = Dec – Feb ; Spring = Mar – May ; Summer = Jun = Aug ; Autumn = Sep – Nov.

Table 4 Number and size of regions for the three regionalisations in England and Wales.

Regionalisation	Type	n	Size (km^2)	
			Mean	**St Dev**
UKCP 50 km	Grid	97*	1,542	920
ACEW	Climatological	68	2,223	1,191
CAMS	Hydrological	116	1,304	815

* Three coastal grid squares containing very small areas of land were excluded from the analysis.

Table 5 ETo variation comparison for three regionalisation methods for England and Wales in January and July.

Statistic	**January**			**July**		
	UKCP 50 km	**CAMS**	**ACEW**	**UKCP 50 km**	**CAMS**	**ACEW**
n	95	116	68	95	116	68
$SS_{BR}^{(k)}$	30267	22021	22144	460487	437739	451999
$SS_{\mathrm{Re}\,s}^{(k)}$	10535	19088	18965	48916	72500	58240
$d.f_{\mathrm{Re}\,s}^{(k)}$	6160	6144	6192	6160	6144	6192
FBR (p-value)	188.3 (10^{-6})	61.63 (10^{-6})	107.9 (10^{-6})	616.9 (10^{-6})	322.6 (10^{-6})	717.3 (10^{-6})
Between regions variation	74% [a]	54% [b]	54% [b]	90% [c]	86% [d]	87% [e]
Within regions variation	1.7	3.1	3.1	8.0	11.8	9.4
Mean Absoulte Deviation (mm month^{-1})	1.0[a]	1.1[b]	1.2[b]	2.0[c]	2.4[d]	2.2[e]

[a] Values with the same superscript are not significantly different.

Figure 1 Maps showing the (a) agroclimatic regions (ACEW) (b) UKCP_{50} grid squares and (c) UKMO_5 grid squares for England and Wales. The markers show the weather stations used in the analysis.

Figure 2 Relationship between $\mathrm{ETo}_{\mathrm{site}}$ and Agricultural Climate of England and Wales (ACEW) PT (mm month^{-1}), by month.

Figure 3 Relationship between $\mathrm{ETo}_{\mathrm{site}}$ and UKCIP 50 km grid resolution dataset (UKCIP_{50}) (mm month^{-1}).

Figure 4 Relationship between $\mathrm{ETo}_{\mathrm{site}}$ and UK Met Office 5 km grid resolution dataset (UKMO_5) (mm month^{-1}) by month.

Figure 5 Relationship between $\mathrm{ETo}_{\mathrm{site}}$ and PT for 15 stations in England and Wales, by month.

Figure 6 Comparison of mean (1981 – 2010) monthly (July), seasonal (April - September) and annual ETo (mm), based on UKMO_5 data for England and Wales.

Figure 7 Mean Absolute Deviation (MAD) (mm month^{-1}) in ETo for three regionalisations in a) January and b) July.

Scale impacts on spatial variability in reference evapotranspiration

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