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Estimating hourly variation in photosynthetically active radiation across the UK using MSG SEVIRI data

P Pankaew, E J Milton and J Dash

Geography and Environment, University of Southampton, Highfield, Southampton
SO17 1BJ, UK

E-mail: P.Pankaew@soton.ac.uk

Abstract. The amount of photosynthetically active radiation (PAR) reaching the Earth's surface is a key input variable in most gross primary productivity models. However, poor representation of PAR due to large pixel size or limited temporal sampling is one of the main sources of uncertainty in such models. This paper presents a method to estimate PAR at up to 1 km spatial resolution at a regional to global scale. The method uses broadband radiance data (400-1100nm) and per-pixel estimates of relative cloud cover from a geostationary satellite to estimate the amount of PAR reaching the Earth's surface at high spatial and temporal resolution (1-2 km and hourly). The method was validated using data from 54 pyranometers located at sites across the UK. Hourly averaged PAR over the range 400-1400 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was estimated with a mean bias error = 5.01 $\mu\text{mol m}^{-2} \text{s}^{-1}$ ($R^2 = 0.87$), providing a source of accurate data for high resolution models of gross primary productivity.

1. Introduction

The amount of photosynthetically active radiation (PAR) reaching the Earth's surface is important because it is one of the key factors driving plant productivity and therefore the production and storage of organic carbon [1]. Despite its importance, there are relatively few places around the world where PAR is routinely measured, unlike other meteorological variables such as solar irradiance. We can estimate the amount of PAR at the top of the atmosphere based on the amount and spectral distribution of solar irradiance, but estimating the proportion reaching the ground is difficult because that is affected by the optical properties of the atmosphere, and in particular the presence of cloud which varies temporally and spatially.

Satellite remote sensing was identified as a possible method to measure downwelling irradiance in the 1960s [2], and various methods have been developed since then [3]. Some methods are based on physical modelling of light transmission through the atmosphere whereas others rely on empirical relationships between irradiance measured at the ground and the top-of-atmosphere (TOA) radiance measured by a satellite sensor. The same approaches have also been used to estimate downwelling PAR, taking into account the narrower range of wavelengths compared with broadband irradiance [4-6]. Most of these methods aim to estimate the average PAR over daily or monthly periods, but for many purposes, such as plant productivity modelling in environments with rapidly changing cloud cover, finer temporal resolution is required. One way to achieve this would be to use data from a geostationary satellite rather than one in near-polar orbit. Janjai and Wattan [7] developed such a method for Thailand, but applying their method to the UK is more challenging because mid-latitude



areas are viewed off-nadir from geostationary orbit and cloud cover in maritime temperate areas is highly variable in time and space.

The UK has a few meteorological stations that measure PAR, but not enough to provide a detailed map of the spatial variability of PAR across the whole of the country at the temporal sampling intervals required for biophysical modelling. The aim of this study was to develop and test a method to use data from a geostationary satellite to estimate the average hourly PAR across the whole of the UK at a spatial resolution of up to 1 km. The method developed has two parts. First, an empirical relationship was established between global broadband irradiance and global PAR, so that the amount of PAR may be inferred from data collected by the broadband SEVIRI HRV instrument. Second, equations describing the transfer of radiation through the atmosphere were used to estimate the PAR at ground level based on data from SEVIRI HRV.

2. Data sources

2.1. Satellite data

2.1.1. Broadband irradiance. The SEVIRI instrument on board the Meteosat Second Generation (MSG) satellite has a High Resolution Visible (HRV) channel which provides measurements of broadband spectral irradiance (400-1100 nm) every 15 minutes from pixels with a nominal sub-satellite sampling distance of 1 km. The MSG satellite is positioned over the equator, giving SEVIRI HRV an instantaneous field-of-view 2-3 km at the latitude of the UK. Data from the whole hemisphere are resampled during preprocessing and provided as 1 km pixels in a stereographic map projection. For this study the area covering the UK was selected and re-projected to a cylindrical projection for ease of overlay with other geographical data sets (figure 1). SEVIRI HRV data covering the period 2005-2012 were used in this study (approximately 30,000 images).

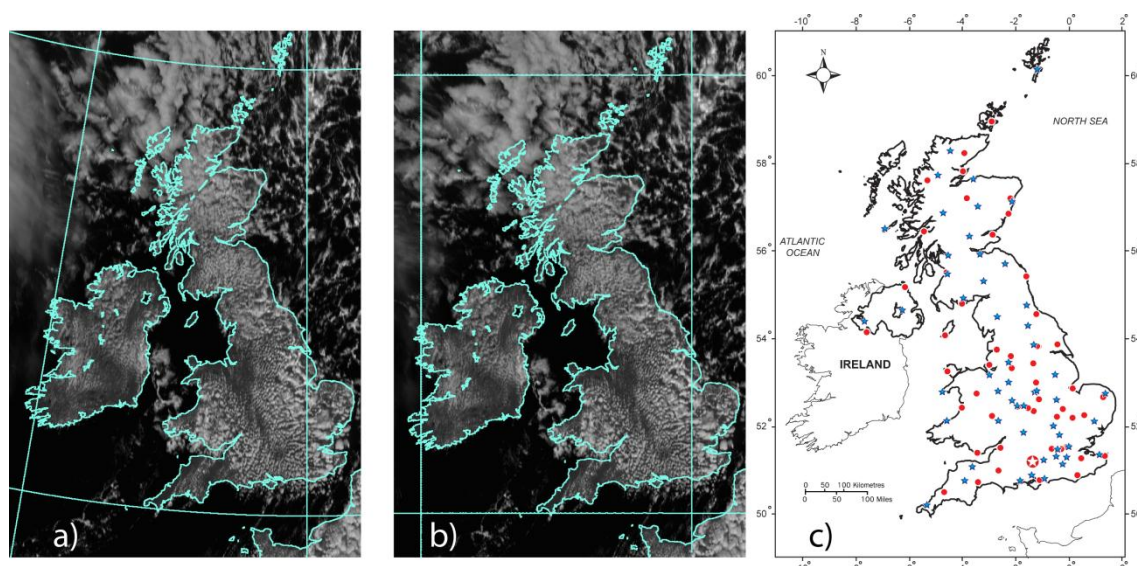


Figure 1. The SEVIRI subset (Fig 1a), transformed to cylindrical map projection (Fig 1b) and the distribution of pyranometer sites used for generating the model (★) and for validation (●). The location of the Chilbolton Facility for Atmospheric & Radio Research is shown in Fig 1c (★).

2.1.2. Ozone data. Data from the Earth Probe Total Ozone Mapping spectrometer (EP/TOMS) and the Ozone Measurement Instrument (OMI) were acquired for the same period as the MSG data to provide information on the amount of ozone in the upper atmosphere as this would affect the absorption in the PAR region.

2.2. Ground data

2.2.1. Pyranometer network. The UK has a dense network of meteorological stations many of which measure global broadband irradiance using Kipp and Zonen CM21 pyranometers. For this study, a total of 108 pyranometer stations, each having at least 6,000 hours of recorded data between March 2005 and March 2012 were selected and randomly assigned to two equal sized groups, one for model development, one for validation (figure 1c).

2.2.2. PAR data. A Li-Cor Biosciences LI-190SA quantum sensor was installed for 12 months specifically for this study at the STFC Chilbolton Facility for Atmospheric and Radio Research (CFARR) (latitude 51.14° N, longitude 1.44° W) in close proximity to a Kipp and Zonen CM21 pyranometer from the UK network of pyranometers (figure 1c).

3. Modelling

3.1. Principles of model

We considered that the main atmospheric influences on the amount of PAR received at the ground surface are the amount and type of cloud, molecular (Rayleigh) scattering and absorption due to ozone, therefore:

$$Q_t = Q_{ex} T_{Q,c} T_{Q,r} T_{Q,oz} \quad (1)$$

where Q_t is the global PAR at the Earth's surface ($\mu\text{mol m}^{-2} \text{s}^{-1}$), Q_{ex} is the extraterrestrial PAR (TOA) and $T_{Q,c}$, $T_{Q,r}$ and $T_{Q,oz}$ are the transmittance of PAR due respectively to cloud, Rayleigh scattering and ozone.

3.2. Extraterrestrial PAR

This was calculated from the spectral solar irradiance at the top of the atmosphere based on data from [8] and converted from energy units (Wm^{-2}) to photosynthetic photon flux density (PPFD) units ($\mu\text{mol m}^{-2} \text{s}^{-1}$).

3.3. Effect of molecular scattering on PAR transmission

This was based on the optical depth (air mass), taking account of the solar zenith angle.

3.4. Effect of ozone absorption on PAR transmission

Ozone in the upper atmosphere absorbs in the region between 375-650 nm (Chappuis bands), which overlaps with the PAR region. Correction for this was based on data from [8].

3.5. Atmospheric transmittance due to cloud

The transmittance due to cloud ($T_{Q,c}$) was derived from the reflectance of cloud ($R_{Q,c}$), assuming no absorption within cloud:

$$T_{Q,c} = 1 - R_{Q,c} \quad (2)$$

therefore

$$R_{Q,c} = 1 - [T_{Q,r} T_{Q,oz}] \quad (3)$$

and

$$R_{Q,c} = 1 - [(Q_t / Q_{ex}) / (T_r T_{oz})] \quad (4)$$

where T_r is the transmission due to Rayleigh scatter and T_{oz} is the transmission due to ozone (both unitless).

Data from the 54 ground stations were transformed from broadband irradiance to PAR using the relationship established at the field site (Section 2.2.3) and used in equation (4) to provide estimates of the reflectance of cloud. A relationship was then established between $R_{Q,c}$ and an index of cloud reflectance from the SEVIRI data, calculated as:

$$R_{sat,c} = (DN - DN_{min}) / (DN_{max} - DN_{min}) \quad (5)$$

where $R_{sat,c}$ is the reflection due to cloud, DN is the digital number from the satellite data, DN_{min} is the minimum of the digital number and DN_{max} is the maximum of the digital number. The DN_{min} at each pixel is selected from the minimum satellite data at noon. The DN and DN_{max} at different positions and times have different incident zenith angle and reflected zenith angles, so the data were

split into groups based on view zenith angle (θ_z). Table 1 summarises the relationships found for the different θ_z , and it is clear that the accuracy of the model is best at low solar zenith angles, therefore data collected with $\theta_z > 60^\circ$ were excluded from the analysis. This means that we cannot estimate PAR across the UK during the winter months, but this is generally not necessary for plant growth models.

Table 1. Linear relationships between $R_{\text{sat,c}}$ and $R_{Q,c}$ for various solar zenith angle classes.

θ_z ($^\circ$)	Slope term	Intercept	R^2
20-30	$0.9604 * R_{\text{sat,c}}$	0.0545	0.65
39-40	$0.8159 * R_{\text{sat,c}}$	0.1077	0.56
40-50	$0.8227 * R_{\text{sat,c}}$	0.1043	0.53
50-60	$0.7969 * R_{\text{sat,c}}$	0.1308	0.41

4. Results

4.1. Relationship between global PAR (Q_t) and global irradiance (S_t)

A review of the literature suggested that PAR in PPFD units ($\mu\text{mol m}^{-2} \text{s}^{-1}$) is typically twice that of solar irradiance measured in energy units (W m^{-2}), but also that this conversion factor could be sensitive to atmospheric conditions. Data from the PAR sensor and pyranometer co-located at the CFARR between April 2011 and February 2012 are shown in figure 2. The strong linear relationship ($R^2 = 0.99$) showed no evidence of variability over time or with atmospheric conditions, so the conversion factor $1.9455 \mu\text{mol m}^{-2} \text{s}^{-1} = 1 \text{ W m}^{-2}$ was used for the rest of this research.

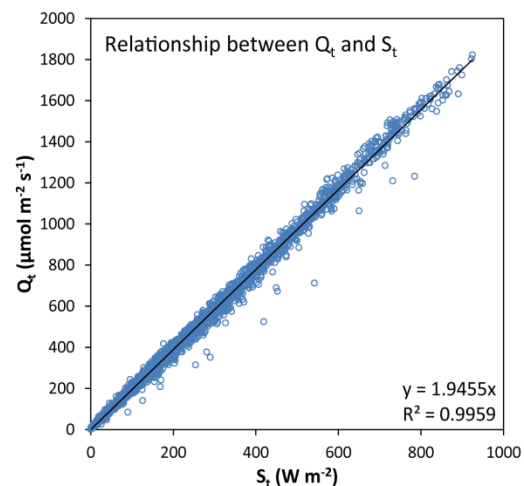


Figure 2. (right) Measured relationship between global PAR (Q_t) and global irradiance (S_t).

4.2. Validation of the model

This was achieved by comparing the PAR calculated using the model with that measured at each of the 54 pyranometer stations that had not been used to generate the model, based on the conversion factor between Q_t and S_t derived in Section 4.1. The results of the validation are shown for hourly average PAR (figure 3a) and monthly average PAR (figure 3b).

The monthly averages show a very good correspondence ($R^2 = 0.98$, mean bias error = $-0.01 \text{ mol m}^{-2} \text{ month}^{-1}$). The hourly data show a larger bias and more scatter, would still be very useful for modelling purposes ($R^2=0.87$, mean bias error = $5.01 \mu\text{mol m}^{-2} \text{s}^{-1}$).

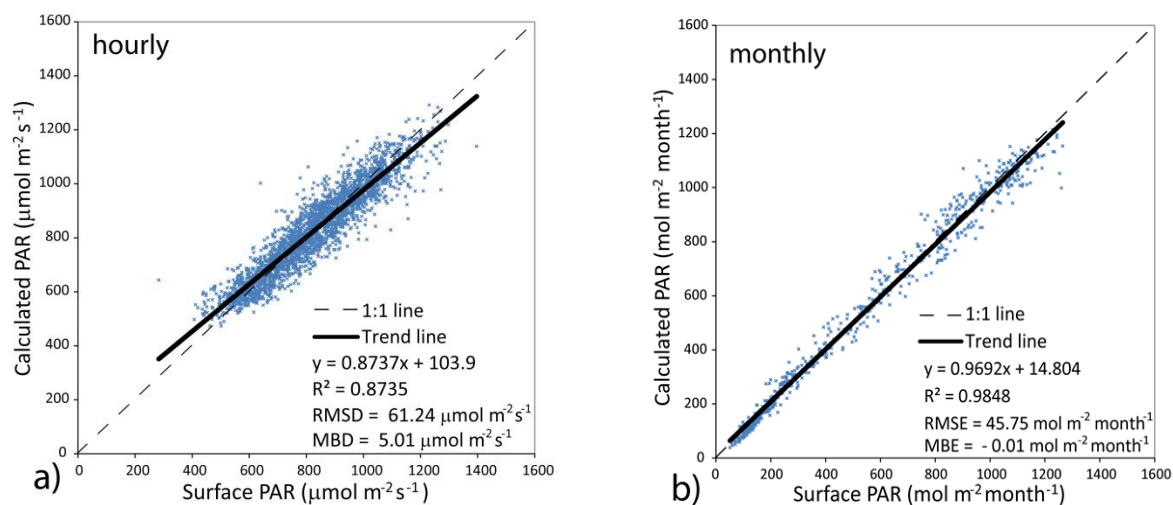


Figure 3. Comparison between modelled PAR and that measured at 54 independent sites (figure 3a, hourly averages, figure 3b, monthly averages).

5. Application to mapping PAR across the UK

The validated model was used to produce a map of PAR over the whole of the UK. Figure 4 shows an example of PAR averaged over each hour of the growing season (March to September). The broad pattern of PAR across the UK is as expected, with higher values in southern England than in the northern England and Scotland, but superimposed upon this there is much local variability. Coastal areas in southern Scotland show relatively high values in May and June; the interior of Wales has relatively low PAR in July and August; and even within the sunny south-west of England there are areas of relatively low PAR at certain times.

PAR is a key input variable in most of the ecosystem gross primary productivity (GPP) models. However, at present there are no standardised products available that provide regular high spatial and temporal resolution observations of PAR. Therefore, most of the remote sensing based regional/global estimates of primary productivity rely on coarse scale interpolated data (for example, the MODIS GPP product (MOD17GPP) uses a PAR data at $1^\circ \times 1^\circ$ spatial resolution; [9]). The poor representation of PAR in these models is identified as one of the main source of uncertainty in the model prediction of GPP [10]. The proposed method provides the potential opportunity to generate PAR at 1 km spatial resolution at a regional to global scale which is at a comparable spatial resolution to other model inputs, thus it would help to reduce uncertainty of global carbon estimation.

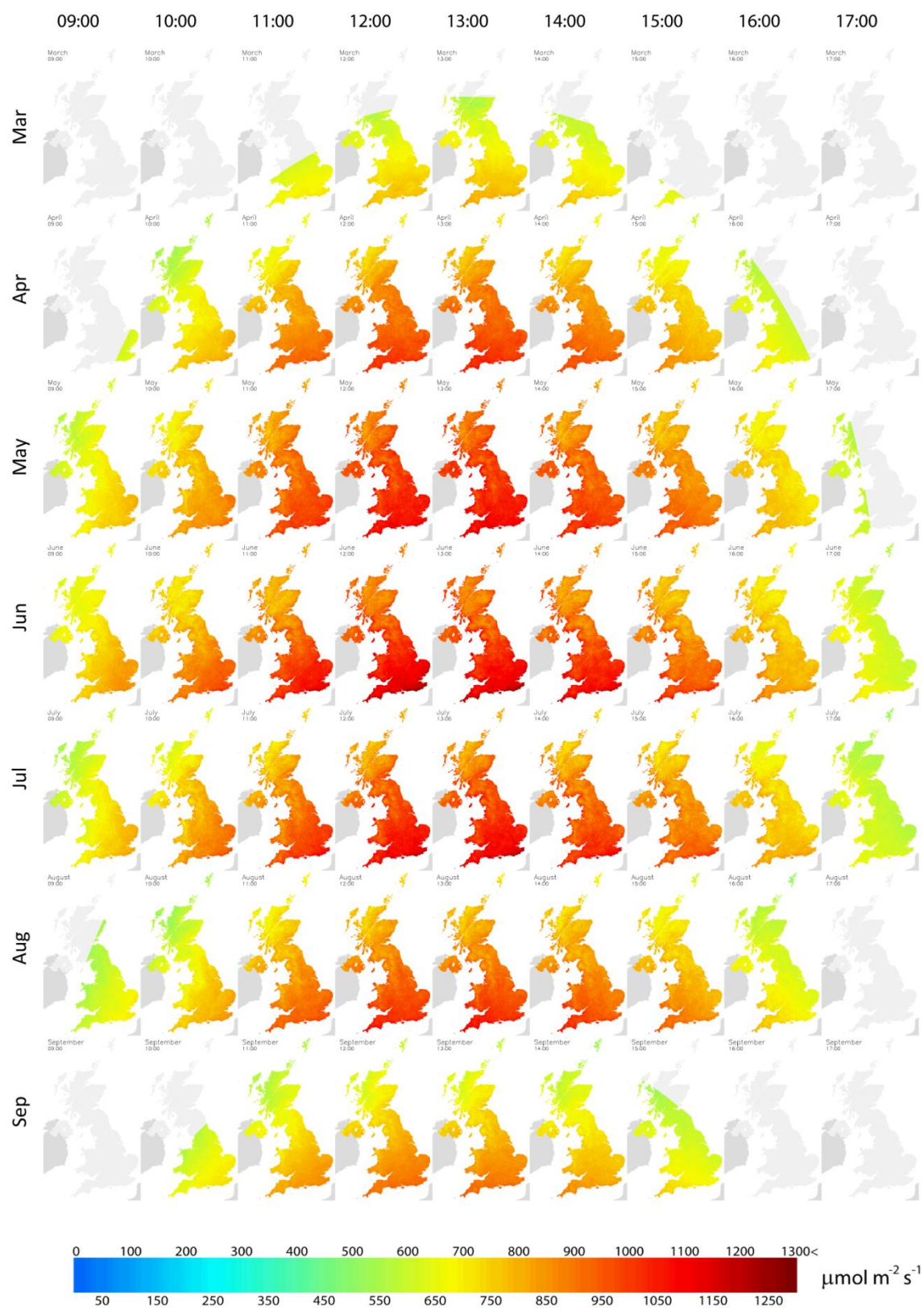


Figure 4. Average hourly distribution of PAR throughout the growing season across the UK estimated using the model described in this paper.

6. Conclusion

A method has been described to calculate incident PAR based on data from a broadband sensor on a geostationary satellite. Experimental data were used to establish a relationship between broadband irradiance and PAR, and a simple radiative transfer model used to characterise the main properties of the atmosphere. The method was validated using independent ground data, and was used to produce a map of hourly PAR throughout a growing season across the UK. This is the first time such a map has been produced for the UK, and it will provide valuable information for the next generation of plant productivity models.

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