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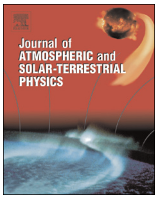

An improved technique for global solar radiation estimation using numerical weather prediction

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ABSTRACT

Global solar radiation is the driving force in hydrological cycle especially for evapotranspiration (ET) and is quite infrequently measured. This has led to the reliance on indirect techniques of estimation for data scarce regions. This study presents an improved technique that uses information from a numerical weather prediction (NWP) model (National Centre for Atmospheric Research NCAR's Mesoscale Meteorological model version 5 MM5), for the determination of a cloud cover index (CI), a major factor in the attenuation of the incident solar radiation. The cloud cover index (CI) together with the atmospheric transmission factor (K_T) and output from a global clear sky solar radiation were then used for the estimation of global solar radiation for the Brue catchment located in the southwest of England. The results clearly show an improvement in the estimated global solar radiation in comparison to the prevailing approaches.

1. Introduction

A deeper understanding of hydrological cycle is required so as to address the issues of water scarcity. Evapotranspiration (ET), which is a pivotal part of the hydrological cycle, is directly affected by the solar radiation. Therefore, solar radiation is the driving force behind the hydrological cycle (Sinokrot and Stefan, 1993; Wigmosta et al., 1994; Kustas et al., 1994; Cline et al., 1998; Pomeroy et al., 2003). Knowledge of solar radiation or more specifically, the global solar radiation is also used in a wide variety of applications in soil physics, engineering, solar energy studies, crop yield estimation as well as in the understanding the health problems associated with human beings and animals (East, 1939; McGrath et al., 2002). Other applications include architectural design of buildings, solar heating systems, solar powered cars and engines, skin cancer research as well as some weather and climate prediction models (Badescu, 2008). Because of its infrequent measurement, availability of reliable and requisite global solar radiation information has always been a challenge for hydrologists and water managers (Richardson, 1985; Hook and McClendon, 1992; Badescu, 2008). Compared to other meteorological variables like temperature and precipitation, global solar radiation is infrequently measured (Liu and Scott, 2001; Weiss and Hays, 2004). For example in the USA, the ratio of spatial density of weather stations that measure solar radiation to the ones that measure temperature is of the order of 1:100, while for the rest of the world it is 1:500 (Badescu, 2008). For these very reasons, reliance on indirect techniques of estimation is gaining importance nowadays especially for data scarce regions.

Modelling of global solar radiation dates back to the start of the 20th century when Kimball (1919) developed a relationship between average daily radiation and sunshine duration using the measured data of several locations within US. Angstrom (1924) proposed a simple empirical relationship using the measured data from Stockholm. The Angstrom relation was later modified by Prescott (1940) who used a more generalised Agnot's value from Brunt (1934). Over the years researchers have also suggested a nonlinear relationship between sunshine duration and global solar radiation (e.g. Morton, 1983;Suehrcke, 2000; Yang and Koike,

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2005). On the other hand some have also suggested complex spectral radiative transfer models e.g. (Leckner, 1978; Dozier, 1980; Bird, 1984); SMARTS2 (Gueymard, 1995) and REST2 (Gueymard, 2008). Owing to data availability, hydrologists have also been using cloud based models (Supit and van Kappel, 1998; Ehnberg and Bollen, 2005) or temperature based models (Bristow and Campbell, 1984; Bechini et al., 2000) or a combination of temperature, humidity and precipitation (Thornton and Running, 1999). But still the results have not been better than a well calibrated sunshine based simplified model (Iziomon and Mayer, 2001; Podesta et al., 2004). Models based upon other widely available meteorological data, that include air temperature, relative humidity, barometric pressure and sunshine duration, have also been developed like the Meteorological Radiation Model (MRM) (Kambezidis and Papanikolaou, 1989; Kambezidis and Papanikolaou, 1990; Kambezidis et al., 1993; Kambezidis et al., 1997; Psiloglou and Kambezidis, 2007; Kambezidis and Psiloglou, 2008). Others have used Artificial Neural Networks for the estimation of solar radiation (Remesan et al., 2008; Mohandes et al., 1998; Lopez et al., 2001; Rehman and Mohandes, 2008; Shamim et al., 2010).

Some indirect techniques have also been developed in the past that make use of satellite imagery (Gautier et al., 1980; Tarpley, 1979; Hay, 1993) or numerical weather prediction. Satellite imagery based models range from the purely empirical to the physically rigorous models (Perez et al., 2002). Hybrid models that couple both the physical and empirical aspects have also been developed over the years as elaborated in Schmetz (1989), Noia et al. (1993), Pinker et al. (1995) and Perez et al. (2001). On the other hand, satellite imagery has also been used for the development of solar radiation maps (Jervase et al., 2003; Kandirmaz et al., 2004; Polo et al., 2008) and for the estimation of global sunshine duration (Kandirmaz, 2006; Shamim et al., 2012).

As for the Numerical Weather Prediction (NWP) methods, the Regional Atmospheric Modeling System (RAMS) (Walko and Tremback, 1996) of Colorado State University, the Advanced Regional Prediction system (ARPS) of the University of Oklahoma (Xue et al., 1995) and the Mesoscale Modeling system (MM5) (Grell et al., 1995) of PSU/NCAR, have been in use over the years for global solar radiation estimation. The simple models make use of the surface derived meteorological data such as sunshine duration (Iqbal, 1983; Janjic, 1990; Yang et al., 2001) or cloud fraction (Atwater and Ball, 1981). But the dilemma is that these models cannot be applied for NWP systems as sunshine duration and cloud cover are not model prognostic variables.

In this paper, an attempt has been made to address this issue by developing a simple global solar radiation model using NWP based MM5 output. Firstly a clear sky global solar radiation models is calibrated to determine the global clear sky radiation at the catchment of interest. Then, the ability of MM5 to predict two most important variables that influence cloud formation, air pressure and relative humidity is assessed at the ground surface. Once this has been achieved, MM5 outputs of pressure and relative humidity, are used for computation of cloud cover index (CI) which is thereafter used for the determination of atmospheric transmissivity K_T. The atmospheric transmissivity together with the clear sky global solar radiation and cloud cover index (CI) is then utilised for the computation of global solar radiation under all skies. A comparison has also been made with the previously developed approach, proposed by Yang and Koike (2002) that also utilises upper air information for computation of global solar radiation.

2. Methodology

The methodology of estimation of global solar radiation comprises of following steps

i. Computation of clear sky global solar radiation
ii. MM5 simulations
iii. Computation of Cloud cover index (CI)
iv. Global solar radiation estimation

2.1. *Clear sky radiation estimation*

2.1.1. *For new proposed model*

Clear sky global solar radiation for the new improved methodology was estimated using Meteorological Radiation Model-version 5 (MRM-v-5) (Psiloglou and Kambezidis, 2007; Kambezidis and Psiloglou, 2008). Accordingly, clear sky global solar radiation, $\varphi_{clearsky}$ is the summation of beam and diffused components given by (Bird and Hulstrom, 1981a,b) as

$$\varphi_{clearsky} = \varphi_b + \varphi_d \tag{1}$$

where, φ_b represents the beam component and φ_d represents the diffuse component of global solar radiation. Bird and Hulstrom, (1981b), Psiloglou and Kambezidis (2007) gave the following equation for the computation of φ_b as

$$\varphi_b = \varphi_{ext} \ \mathrm{sinh} \ T_a T_r T_o T_{mg} T_w \tag{2}$$

where, φ_{ext} is the extraterrestrial radiation for hourly time intervals for the station in question and further details can be found in FAO (1998), 'h' is the solar elevation angle in radians, T_a is the aerosol total extinction (scattering and absorption) (Psiloglou and Kambezidis, 2007), T_r is the optical transmittance due to Rayleigh scattering, T_o is the optical thickness due to ozone absorption, T_{mg} is the optical transmittance due to mixed gases and T_w is the optical transmission due to water vapours.

The optical transmittance due to Mie scattering T_a as given by Yang et al. (2001) is

$$T_a = \exp\left\{-m\beta\left[0.6777 + 0.1464m\beta - 0.00626(m\beta)^2\right]^{-1.3}\right\} \tag{3}$$

β is the Angstrom turbidity parameter (range 0.05–0.4) for low to high concentrations. Indicative values of β can be found in Table 1. Computation relations (Yang et al., 2001) for the same are given below

$$\beta = \beta' + \Delta\beta \tag{4}$$

$$\beta' = (0.025 + 0.1 \ \cos \ \phi)\exp(-0.7H/1000) \tag{5}$$

$$\Delta\beta = \pm\,(0.02\text{–}0.06) \tag{6}$$

where, β' represents the annual mean value of turbidity and $\Delta\beta$ is the seasonal deviation from the mean (low in winter and high in summer). In the above equations, ϕ is the geographic latitude and 'H' is the station altitude in metres.

In the above equations, β' represents annual mean value of turbidity and $\Delta\beta$ is the deviation from the mean (low in winter, high in summer).

Transmission factor for seven atmospheric gases (water vapour, H_2O; ozone, O_3; carbon dioxide CO_2; carbon monoxide, CO; citrous

Table 1
Angstrom's turbidity parameter for different atmospheric conditions and visibility ranges (Psiloglou and Kambezidis, 2007).

Atmospheric conditions (CM)	β	Visibility, V (km)
Clean	0.05	340
Clean	0.1	28
Turbid	0.2	11
Very turbid	0.4–0.5	< 5