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A new approach to estimate the spatial distribution of solar radiation using topographic factor and sunshine duration in South Korea

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ABSTRACT

Solar radiation is one of the important renewable resources, currently scientists are taking their interest in. Accurate solar radiation data is not only required for solar-power management but also is a vital input parameter in different biogeochemical and atmospheric models. But there are inadequate number of stations measuring solar radiation in comparison to stations dedicated for sunshine duration, temperature, humidity etc. Therefore, to overcome this problem, an empirical model is developed to estimate solar radiation from sunshine duration data over South Korea. As more than 50% of the area in Korean peninsula have a complex terrain, a topographical factor is applied to modeled data. Thereafter a map presenting monthly mean variation in incoming solar insolation is constructed using ordinary kriging method. The influence of topographical features like slope and aspect is found to be higher in winter than summer. Solar radiation is highest in May and lowest in December over Korea. Spatial variation of incoming radiation is mainly influenced by topographical and atmospheric features whereas latitudinal gradient is almost insignificant.

1. Introduction

The growing threat of global warming and exhaustion of current fossil fuel resources have motivated the global scientific community to search and develop other non-conventional energy sources like solar energy. Although in each second the amount of solar energy reaching the earth surface is 10,000 times higher than the current daily energy requirements, it constitute only 0.1% of total world consumption, mainly due to technical inefficiency and large developmental cost [1]. However, recently the importance of solar energy has again been highlighted, due to increasing pressure from Intergovernmental Panel on Climate Change (IPCC) to reduce the global carbon dioxide emission. Besides a number of human economical activities like building design, land management, agriculture and forestry ultimately depend on incoming solar radiation. It is also the major driving force behind earth's different biological and atmospheric phenomenon. Therefore, besides assisting in site selection, planning and simulation of solar energy system, accurate insolation data is also a key component in undertaking many renewable, hydrological and agricultural studies. Moreover a precise map of available solar energy is extremely important in decision making support system not only for selection of right land for related facilities but also for maximizing the efficiency of solar energy transfer. A simple interpolation method can be used to generate an insolation map from ground based measurements [2–6]. But in most areas of the world, solar radiation measuring stations are not easily available due to financial, technical or institutional limitations [7]. The insufficient number affects the spatial and temporal resolution of such image which in turn leads to incorrect system sizing and unnecessary use of conventional energy. The number of weather stations recording daily radiation is minor compared to the number which records other meteorological parameters. The global ratio between stations measuring radiation and those measuring temperature may be as low as 1:500 [8]. In South Korea there are approximately 460 Automatic Weather Stations (AWS) and 96 weather stations for measuring temperature and precipitation, among which solar radiation is measured only in 22 weather stations. Hence, an empirical model relating solar radiation with other atmospheric parameters can be helpful in generating more set of points with available data which successively can enhance the resolution of insolation map. There are many studies to estimate solar radiation based on empirical relationships between the observed solar radiation and the meteorological elements. The empirical models are mainly based on temperature [8–13] cloudiness [14–16] and sunshine duration [5,17–23] or combination of them [24]. The sunshine based

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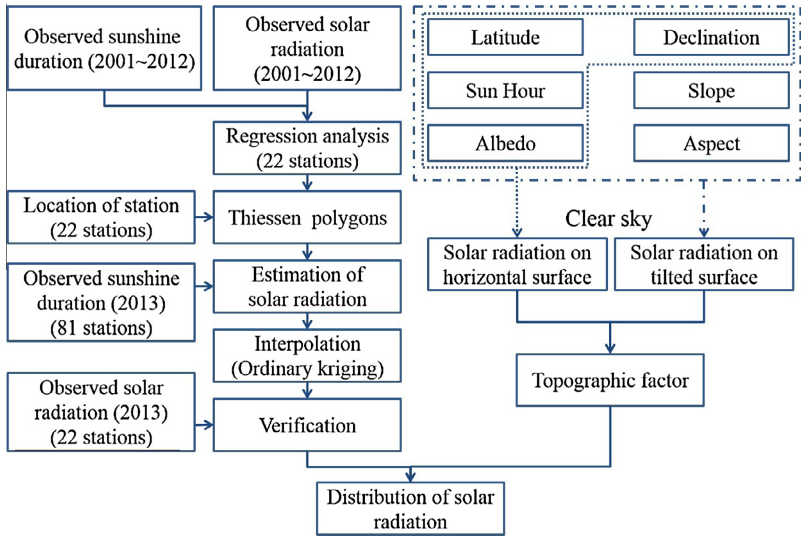

Fig. 1. Flow chart of global solar radiation distribution model.

methods are generally more accurate and therefore are commonly used for estimating solar radiation by many researchers [25–27].

However, at the landscape scale, variability in elevation, surface orientation (slope and aspect) and shadows cast by topographic features are the major factors modifying the distribution of radiation. Different scientists developed a variety of methodologies to integrate topographical features in estimation of ground radiation. Que et al. [28] studied a distribution model for calculating extraterrestrial solar radiation over rugged terrain based on Digital Elevation Model (DEM). Kumar et al. [29] described the potential solar radiation on any slope and aspect and at many latitudes. Pons and Miquel [30] has developed and evaluated a methodology for obtaining monthly radiation maps based on DEM, field data and GIS tools. Ruiz-arias et al. [31] analyzed the solar radiation model using DEM and topographic characteristics. Having a mountainous terrain, in South Korea the topographic factors can create a strong localized gradient in available solar energy. The slope average in the South Korea is 14.3 degrees, and 45.2% is lowland area with less than or equal to 15 degrees and 30.7% is more than 20 degrees [32]. Thus, for more accuracy in estimating solar radiation it is necessary to consider the topographic conditions such as slope and aspect.

The purpose of the present study is to estimate the regional and temporal distribution of solar radiation over South Korea based on the spatial interpolation of ground data. For this reason, empirical relationships have been developed to derive the solar radiation at horizontal surface using sunshine duration data. The changes in the solar radiation for surface slope and aspect has also been included to investigate the influence of topographic features.

2. Methods and materials

In this section a schematic description of the steps followed to estimate the solar radiation is reported. At first, 22 stations collecting both solar radiation and sunshine data from 2001 to 2012 is selected for regression analysis. After that, the Thiessen polygons are created using these 22 stations. It divided the other 59 stations measuring only the sunshine hours into 22 groups. Each group having only one radiation observing station has the same regression parameters. Thereafter, insolation data over all these 81 stations are taken into account for spatial interpolation. But it only derived the spatial distribution of incoming radiation at horizontal surface. The topographic factor is modeled using the effect of surface slope and aspect on clear sky solar radiation and it is then applied on the interpolated spatial distribution to construct accurate solar radiation data over complex terrain. A simple flowchart summarizing our approach towards the estimation of a precise solar radiation map over South Korea is depicted in Fig. 1.

2.1. Study area

The present study is conducted over the Republic of Korea which occupies the southern portion of the Korean peninsula. It lies between latitudes 33°N and 39°N, and longitudes 124°E and 130°E covering a total area of 100,032 km^2. The South Korea's terrain is mostly mountainous, most of which is not arable. Lowland, located primarily in the west and southeast, make up only 30% of the total land area. Slope average in the South Korea is 14.3 degree, and lowland area with less than 5 degree of slope is only 28.2%. Otherwise, 58.8% of total area is more than 10 degree of slope, 45.2% is more than 15 degree and 30.7% is more than 20 degree [32]. Hence, for accurate measurement of solar radiation consideration topographic conditions such as slope and aspect is extremely essential.

2.2. Regression model

The history of solar energy estimation algorithms using meteorological parameters dates back to 100 years. One of the first work published by Ångström [16] expressed the correlation between global solar radiation and sunshine duration in the sky. Sunshine-based model using Ångström-Prescott equation, when tested for 59 localities covering Europe, Asia, Africa, and North America, showed an average Mean Bias Error (MBE) of only 8.8% [33]. The equation established an empirical relationship between clearness index (K_t) and relative sunshine duration as shown in Eq. (1) [25,26].

$$K_t = \frac{H}{H_0} = a + b\left(\frac{n}{N}\right) \tag{1}$$

Here H is solar radiation on horizontal surface at ground (MJ m^{-2} day^{-1}), H_0 is extraterrestrial radiation on a horizontal surface (MJ m^{-2} day^{-1}), n is hours of sunshine (hour day^{-1}), N is hours of maximum possible sunshine (hour day^{-1}) and a, b are the regression constants to be determined.