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Production of solar radiation bankable datasets from high-resolution solar irradiance derived with dynamical downscaling Numerical Weather prediction model

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ABSTRACT

A bankable solar radiation database is required for the financial viability of solar energy project. Accurate estimation of solar energy resources in a country is very important for proper siting, sizing and life cycle cost analysis of solar energy systems. During the last decade an important progress has been made to develop multiple solar irradiance database (Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI)), using satellite of different resolution and sophisticated models. This paper assesses the performance of High-resolution solar irradiance derived with dynamical downscaling Numerical Weather Prediction model with, GIS topographical solar radiation model, satellite data and ground measurements, for the production of bankable solar radiation datasets. For this investigation, NWP model namely Consortium for Small-scale Modeling (COSMO) is used for the dynamical downscaling of solar radiation. The obtained results increase confidence in solar radiation data base obtained from dynamical downscaled NWP model. The mean bias of dynamical downscaled NWP model is small, on the order of a few percents for GHI, and it could be ranked as a bankable datasets. Fortunately, these data are usually archived in the meteorological department and gives a good idea of the hourly, monthly, and annual incident energy. Such short time-interval data are valuable in designing and operating the solar energy facility. The advantage of the NWP model is that it can be used for solar radiation forecast since it can estimate the weather condition within the next 72–120 hours. This gives a reasonable estimation of the solar radiation that in turns can be used to forecast the electric power generation by the solar power plant.

1. Introduction

The financial issues have an important consideration in the deployment of the solar power plants. The financial considerations involve capital cost and system performance analysis, which is based on the availability of solar resource. The availability of long-time series of solar radiation is vital to meet the need of financial parties. Accurate prediction of solar energy resources over the potential location is very important for proper siting, sizing and life-cycle cost analysis of solar power plant. During the last decade an important progress has been made to develop multiple solar irradiance database (Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI)), using satellite of different resolution and sophisticated models. The United States Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) and the Atmospheric Sciences Research Center (ASRC) at the State University of New York (SUNY)/Albany (USA) were the pioneers in the development of tools and data sources for solar energy during the past decade. The major current platforms used for estimating the solar radiation are based mainly on the Geostationary Operational Environmental Satellites (GOES), which were launched and maintained by the US National Oceanic and Atmospheric Administration (NOAA). Over the past two decades, a series of GOES satellites were launched to cover the entire Western Hemisphere. These satellites collect, every 30 min, high-spatial resolution (∼1 km) visible-channel images of the entire hemispheric, which are converted to hourly estimates of solar resources on a 10 km grid using a semi-empirical approach developed by ASRC. Solar resource data estimation includes both

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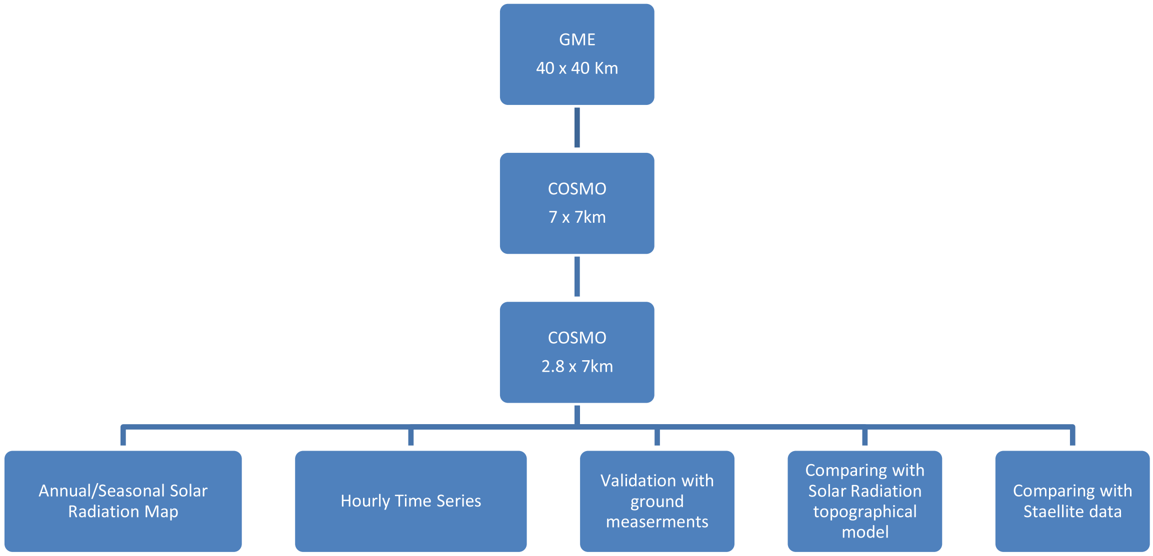

Fig. 1. Flowchart of the methodology used in this study.

GHI and DNI. The model was used to produce the 1998–2005 high-resolution data distributed as part of the US National Solar Resource Data Base (George et al., 2007). Later on and after launching the European Meteosat 5 and 7 geostationary satellites, SUNY adapted the model to estimate solar resources in the Eastern Hemisphere and several solar radiation maps were developed for some of the Eastern countries (Perez et al., 1977; Martins et al., 2007; NASA, 2014).

The solar radiation received at the surface of the ground is the result of energy interaction between the atmosphere and ground surface processes. In the past century, different physical models that formulate these interactions over topographic surfaces for a large spatio-temporal scale were developed (Dubayah, 1991). The first generation of such models, were the Atmospheric and Topographic Model (ATM) (Dubayah, 1992; Dubayah and Rich, 1995), Kumar et al. (1997) and SOLARFLUX (Hetrickw et al., 1993a,b). ATM is a raster based program and it was developed to provide inputs data for hydrological and snowmelt models in hilly area. Such model is explicitly concerned with atmospheric radiations problems. SOLARFLUX is a GIS based model that uses the information related to the topographic characteristics of the surface specified as grid of elevation, latitude, as well as the transmissivity of the atmosphere. Based on this inputs, SOLARFLUX, provides, direct radiation flux, duration of direct radiation, sky view factor, hemispherical projections of horizon angles, and diffuse radiation flux for each surface location. SOLARFLUX has been implemented in the first generation of GIS platform (ARCINFO and GRID GIS) (Hetrickw et al., 1993a,b).

The recent generations of ESRI'S GIS software have implemented the solar radiation analysis tools in the ArcGIS Spatial Analyst extension, which allow the calculation and analysis of the effects of the sun over selected geographic area and for specific periods of time. These analysis tools account for atmospheric effects (but not processes), site latitude and elevation, steepness (slope), compass direction (aspect), daily and seasonal shifts of the sun angle, and effects of shadows cast by surrounding topography.

Despite this sufficient progress in the accuracy of the solar radiation models, and remotely sensed data, the policy maker and the financing community, still consider solar radiation derived from models and satellite as non-bankable solar radiation datasets. The different actors of solar energy systems from engineering and the financing to the operating system, views bankable solar radiation only datasets from land-based measurement, during 10–15 years of datasets, to assess the viability and the capability of the solar power plant to repay its debt. The key consideration in the solar radiation bankable datasets is based on robust assessment of the temporal variability across all time scales of solar radiation that have a direct impact on the power generation and consequently the revenue stream. Therefore, it is crucial to have an accurate, and reliable solar radiation dataset, to reduce the risks associated with solar power plants.

This paper assesses the performance of High-resolution solar irradiance derived with dynamical downscaling Numerical Weather Prediction model with, GIS topographical solar radiation model, satellite data and ground measurements, for the production of bankable solar radiation datasets. Numerical Weather Prediction (NWP) Models, utilize a complex systems of partial differential equations based on the laws of physics, fluid motion, and chemistry, and use a coordinate system which divides the earth into 3D grid. For the purposes of forecasting weather condition, NWP models, calculate winds, heat transfer, solar radiation, relative humidity, and surface hydrology within each grid cell, and the interactions with neighboring cells are used to calculate atmospheric properties in the future.

Over the last decades, concerted efforts have been made to improve the resolution of the NWP models, through the exploitation of the increasing computing power (Ruby Leung et al., 2003). The typical resolution ranges from a few dozen km for General Circulation Models (GCMs) down to a few km for Limited Area Models (LAMs) (Al-Yahyai et al., 2010). GCMs used in meteorology and climatology are usually run at coarse spatial resolution and their output cannot be used for local effect studies, because they are unable to resolve important local scale features such topography and clouds. Downscaling approach were developed since nineties to obtain local scale weather conditions. Two different techniques for downscaling analysis are used. One technique is dynamical downscaling, based on using GCMs output to derive LAMs, which accordingly became able to simulate local weather condition in greater details (Von Storch et al., 1993; Wilby and Wigley, 1997). The other technics is statistical downscaling, where statistical relationship is constructed between observation of atmospheric parameters at large and local scale. Then, the statistical relationship is used on the GCMs data to obtain the atmospheric parameters at local scale form the output of GCMs (Kim et al., 1984; Hessami et al., 2004).

Due to this development, the outputs of NWP models are widely applied in applicable in different areas such as weather

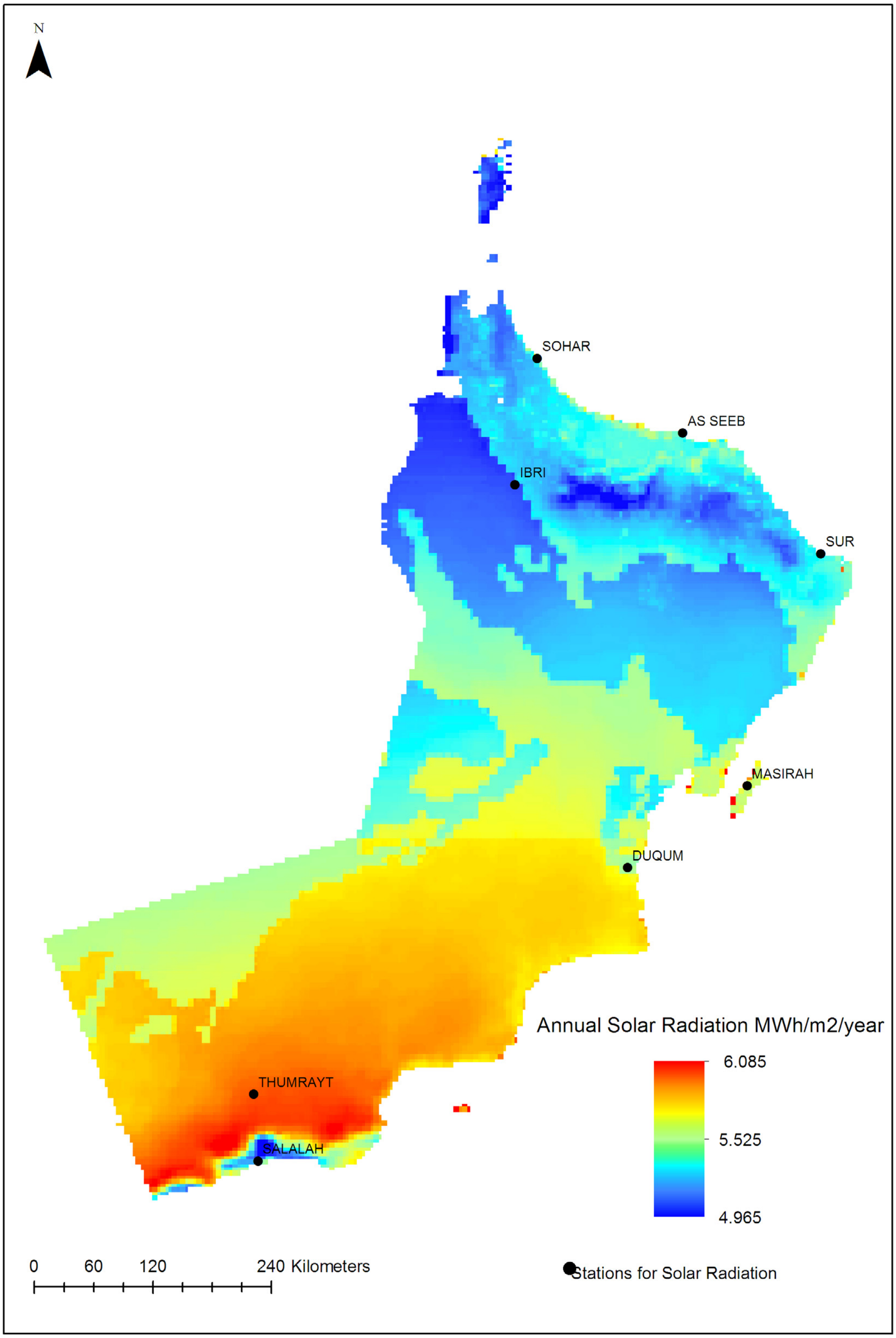

Fig. 2. High-resolution GHI annual pattern for 2009 derived with dynamical downscaling NWP model at 2.8 km.

warming, air quality modeling, aviation, road meteorology, hydrology, and estimation of heating requirement (Christensen and Lettenmaier, 2006; Maraun et al., 2010; Charabi and Al-Yahyai, 2015). Additionally, NWP outputs is also widely used in the estimation of wind power-plant production based on wind forecasts. Incident solar radiation is one of the main meteorological parameter that is usually calculated and forecasted by NWP models. The key consideration for the financial parties in solar energy project is the capital cost and the system performance, which mainly based on the availability of the solar resources.

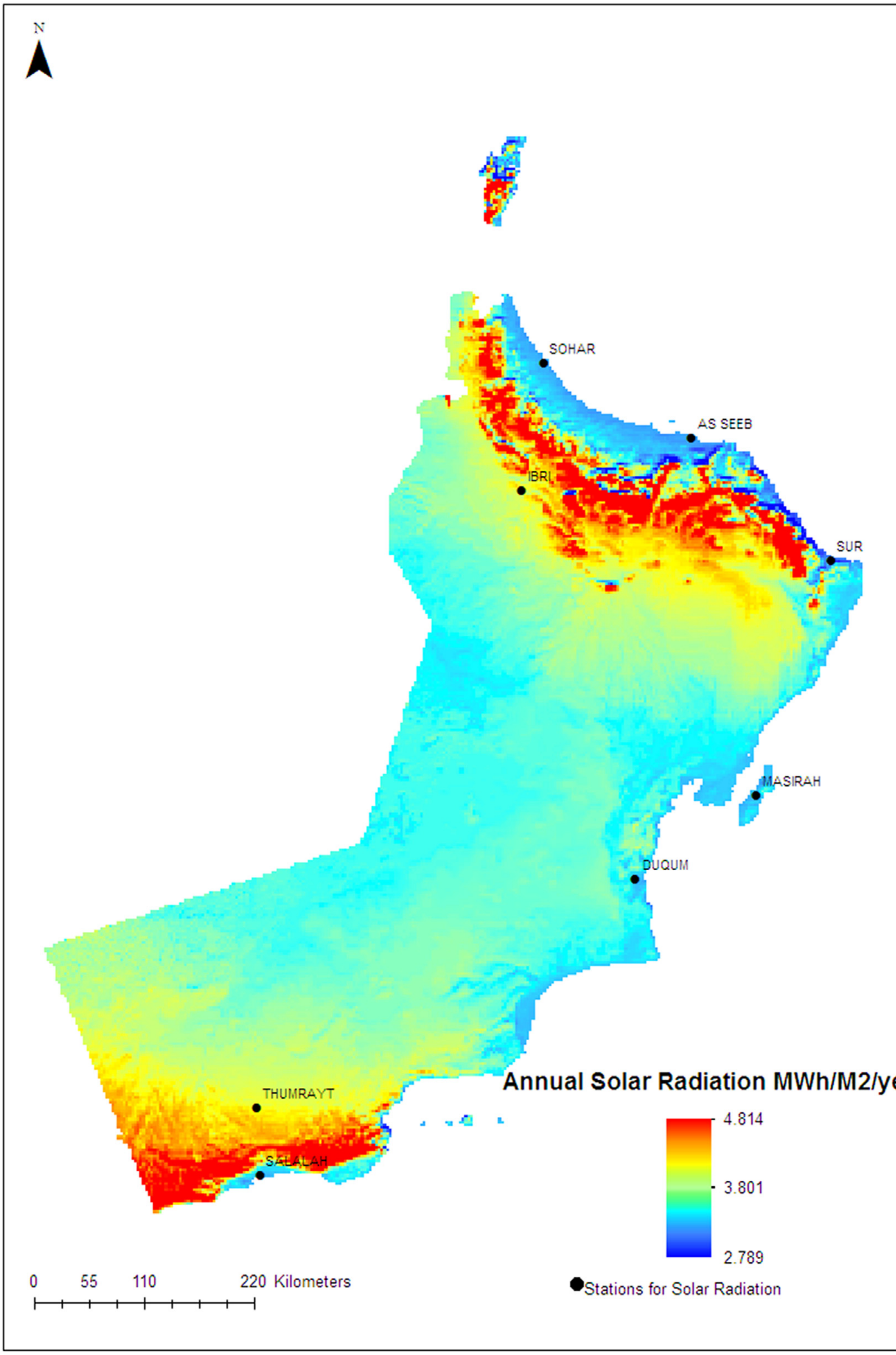

Fig. 3. ArcGIS solar radiation model patterns of annual GHI for 2009 at 2.8 km.

Therefore, this paper focuses on evaluating the performance of High-resolution solar irradiance derived with dynamical down-scaling Numerical Weather Prediction model for the production of bankable solar radiation datasets that meet the requirement of the financial communities for solar energy project portfolios. Few studies have focused on using solar radiation simulated by NWP as a bankable datasets. This paper structured as follow: Section 2 present the methodology and the datasets used in the study. Section 3 presents the results obtained from the simulation of solar radiation from NWP model and compared with GIS topographical solar radiation model, satellite data and ground measurements. Finally, the Section 4 concludes the paper.

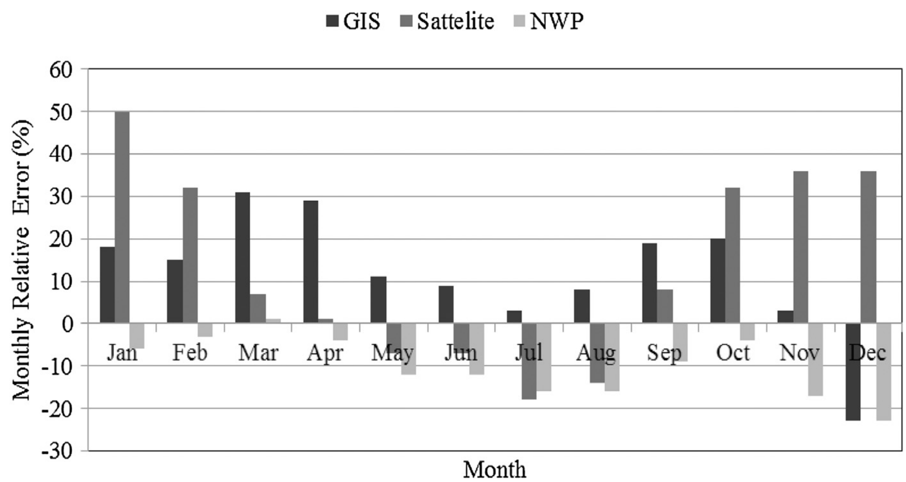

Fig. 4. Monthly relative error for Ibri station.

2. Datasets and methodology

For this investigation, NWP model namely Consortium for Small-scale Modeling (COSMO) is used for the dynamical downscaling of solar radiation. COSMO is a Non-Hydrostatic limited-area numerical weather prediction model for meso-scale. Main prognostic variables are: pressure perturbation, temperature, specific humidity, cloud water, cloud ice, horizontal/vertical wind and several surface/soil parameters. German Global Model (GME) was used to provide the initial and lateral boundary conditions (Al-Yahyai et al., 2010). These conditions provide the meteorological condition of the atmosphere at and surrounding the computational domain. Fig. 1 gives a comprehensive overview of the single NWP model approach for dynamical downscaling of solar radiation. It shows that initial and lateral boundary conditions from GCMs (40 × 40 km) are used to derive and initialize limited area models (7 × 7 km) and covering domain 49.0–64.0E and 13.0–28.0N (Oman) with 241 × 241 grid point and 41 vertical layers. This regional scale prediction is validated with the ground observations and used to derive and initialize a local scale high-resolution model (2.8 × 2.8 km).

Oman situated in southeast corner of Arabian Peninsula, was taken as a reference for this study. Oman has 8 operational meteorological ground stations that measure GHI and DNI scattered around the country as shown by the dots in Fig. 1. The high-resolution GHI derived with dynamical downscaling NWP model, was compared with ESRI ArcGIS Solar Radiation model, which can estimate the GHI and DNI on any point of the Digital Elevation Map of the country. This GIS model requires the information about the transmissivity. This represents a limitation for the GIS Solar radiation model. In this model, single transmissivity value is assumed to be representative of the whole domain without considering different atmospheric processes acting on different parts of the domain. The performance of NWP outputs was also compared with satellite data retrieved for Oman from the online open-source solar radiation data provided by NOAA with a resolution of (1o × 1o) which is equivalent to (111 km × 111 km) (NASA, 2014). All data are estimated as average monthly radiations for the whole year 2009.

3. Results and discussions

The performance of ESRI ArcGIS Solar Radiation model is compared with NWP outputs, satellite data and observations from ground measurements from selected site in Oman. Fig. 2 represents the NWP pattern of annual average of GHI over the study area for 2009. Fig. 3 represents the ArcGIS Solar Radiation model pattern of annual average of GHI over the study area for 2009.

The GIS, NWP and satellite results of selected 5 points located at the same positions of the 5 stations Ibri, Masirah, Salalah, Sur and Thamrait, were compared to the data measured by the ground stations in the same locations for the year 2009. Figs. 4–8 show the monthly average relative errors in the values of the estimated solar radiations compared to the ground measurements.

Notice that, for almost all the 5 stations, the high-resolution GHI derived with dynamical downscaling NWP model gives the most accurate results followed by the ArcGIS Solar Radiation model. The satellite data gives higher monthly average relative errors reaching more than 60% in some cases. Fig. 9 compares the mean annual relative errors for the 3 different models with the ground measurements. It is also clear that the high-resolution GHI derived with dynamical downscaling NWP model is giving better estimation of the total annual radiation than the ArcGIS topographical Solar Radiation model and satellite data.

These results can be explained by the fact that the NWP model takes into account the atmospheric conditions including clouds, temperature, and humidity that affect the solar radiation estimation. In addition, NWP models consider the dynamics of the atmosphere. The dynamical state of the atmosphere is changing from one moment to another. The ArcGIS Solar Radiation model uses the equivalent atmospheric transmissivity for all the land of the country. Therefore, it does not consider the spatial variability that is clearly reflected in Fig. 2. However, the advantage of the ArcGIS is that it takes into account the very high-resolution topography of the area while the topography of NWP model depends on the availability of computational power. The open source Satellite data from NOAA suffer from its low resolution (111 km × 111 km) and thus cannot estimate accurately the value of the solar radiation in a specific point especially if the topography of the land and the sky condition are not homogeneous.

4. Conclusion

This paper assesses the performance of presented the different main models and source of data used for solar radiation estimation. These were compared based on a case study for Oman, which is situated on the Sunbelt of the earth and characterized by high potential of solar energy, using ground measurement, dynamical downscaled NWP model, ArcGIS Solar Radiation model and NOAA satellite open source data. It was found that the dynamical downscaled NWP model gives much more accurate estimation of the monthly as well as the annual average solar radiation at 5 different locations of existing meteorological stations. The ArcGIS Solar Radiation model would give also good estimation of the solar

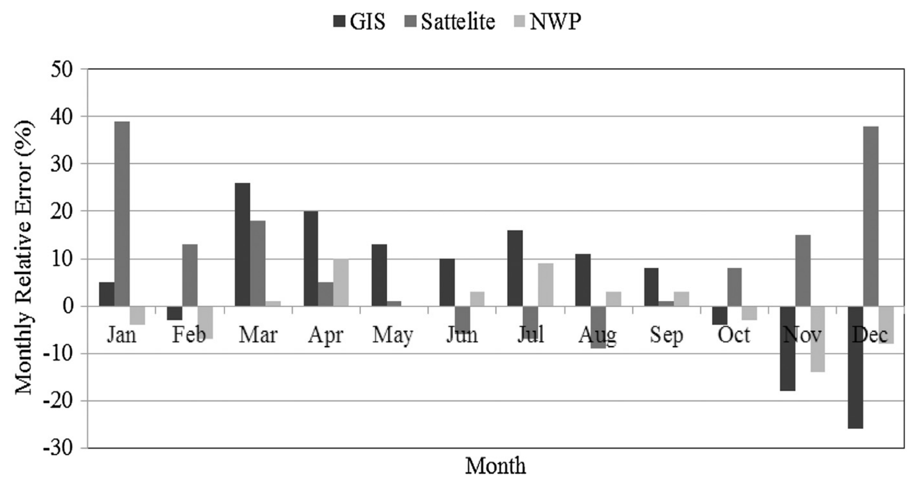

Fig. 5. Monthly relative error for Masirah station.

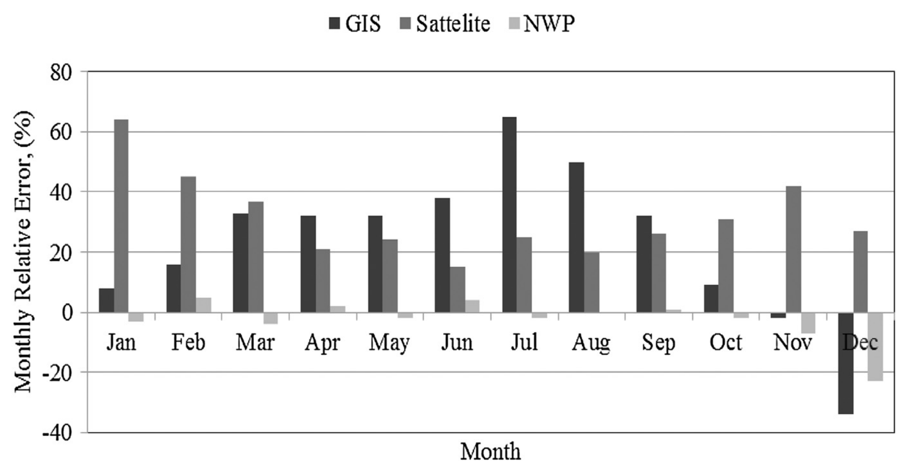

Fig. 6. Monthly relative error for Salalah station.

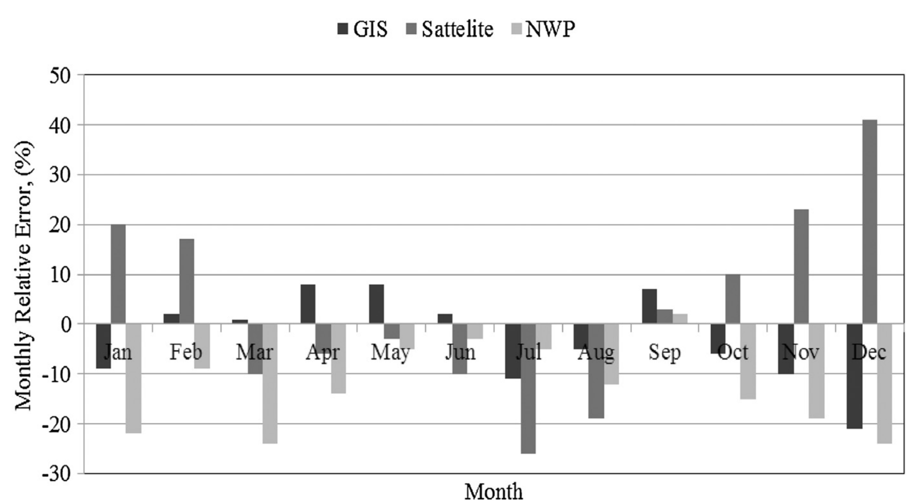

Fig. 7. Monthly relative error for Sur station.

radiation if better information about clear sky and atmospheric transmissivity rate were accurately estimated.

The obtained results increase confidence in solar radiation data base obtained from dynamical downscaled NWP model. The mean bias of dynamical downscaled NWP model is small, on the order of a few per-cents for GHI, and it could be ranked as a bankable datasets. Fortunately, these data are usually archived in the meteorological department and gives a good idea of the hourly, monthly, and annual incident energy. Such short time-interval data are valuable in designing and operating the solar energy facility. The advantage of the NWP model is that it can be used for solar radiation forecast since it can estimate the weather condition

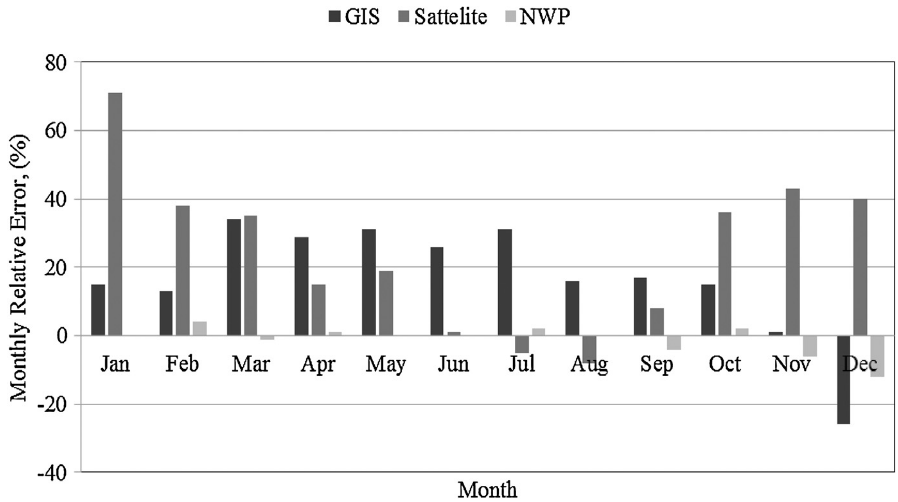

Fig. 8. Monthly relative error for Thumrait station.

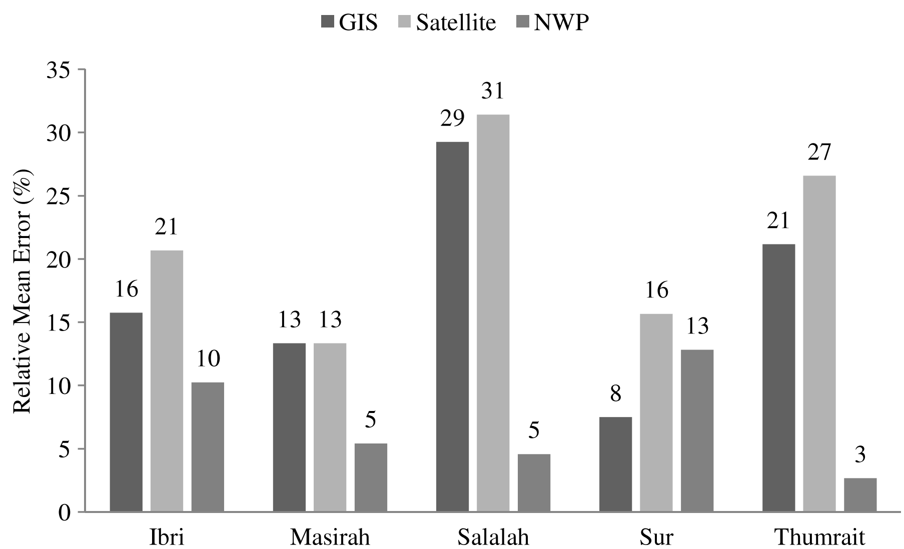

Fig. 9. Comparison of the relative mean error obtained at the selected weather stations.

within the next 72–120 h. This gives a reasonable estimation of the solar radiation that in turns can be used to forecast the electric power generation by the solar power plant.

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