Development, Evaluation and Parallelization of a Spatio-Temporal, Topographic, and Spectral GIS-based Solar Radiation Model

I. D. Dobreva[1, 5], M. P. Bishop[2, 5], J. C. Liu[3, 5], Liang Da[4, 5]

[1]Department of Geography, Texas A&M University, College Station, TX 77843
Telephone: 1-979-845-7141
Email: iliyanad@tamu.edu

[2]Department of Geography, Texas A&M University, College Station, TX 77843
Telephone: 1- 979-845-7998
Email: michael.bishop@tamu.edu

[3] Department of Computer Science and Engineering, Texas A&M University, College Station, TX 77843
Telephone: 1-979-845-8739
Email: liu@cse.tamu.edu

[4] Department of Computer Science and Engineering, Texas A&M University, College Station, TX 77843
Email: liangdaleo@gmail.com

[5]Center for Geospatial Sciences, Applications & Technology (GEOSAT), Texas A&M University, College Station, TX 77843

1. Introduction

Complex mountain topography is the result of coupling of atmospheric, surface, and tectonic processes. Variations in topography influence the surface irradiance and the magnitude of surface process rates given climate change. Existing GIS-based models do not adequately account for spatial, spectral, and temporal dynamics. Therefore, we developed a new spatio-temporal topographic solar radiation model (fig. 1). The model accounts for Earth-Sun orbital dynamics to enable postdiction and prediction of the spatio-temporal variation in surface irradiance for each grid cell. It is also spectral-based, accounting for atmospheric attenuation due to Rayleigh scattering, aerosols, water vapor and ozone as functions of wavelength.

The direct, diffuse-skylight and total components of the surface irradiance are compared to the same components simulated by the solar radiation models implemented in the ArcGIS and GRASS software packages. We also compare results to measured direct and diffuse solar radiation provided in the National Renewable Energy Laboratory (NREL) Solar Radiation Database 1991-2010. In addition, simulations are performed over the Nanga Parbat Massif, Pakistan which is an area that exhibits extreme relief and complex topography. Results indicate there are significant differences in the magnitude of direct irradiance for the solar radiation models. This is attributed to variations in the parameterization of Earth's atmospheric conditions.

These improvements to the existing GIS-based solar radiation models, however, raise the issue of computational time. To understand the speedup potential of the model, a portion of the compute-intensive code in the object-oriented serial program was parallelized on the NVIDIA GK104 Graphical Processing Unit (GPU).

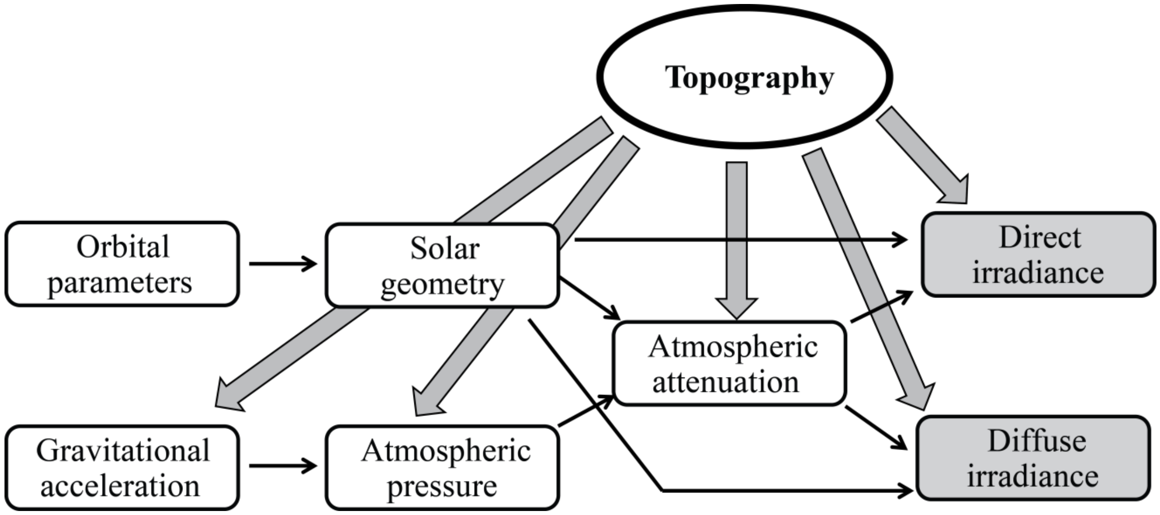

Figure 1. Solar radiation model design.

2. Model Design

The developed solar radiation model accounts for variations in topography because atmospheric properties, such as water content, change as a function of altitude which is represented in the model as geocentric and 3-dimensional. Multi-scale topographic effects are accounted for because the surrounding terrain may block the direct solar radiation or may obscure a fraction of the sky, the later affecting diffuse-skylight irradiance. The model is also spectral to properly account for wavelength-dependent matter-energy interactions.

2.1 Orbital Parameters

The solar energy reaching the top of the atmosphere is a function of Earth-Sun orbital parameters, the solar constant and the latitude on Earth surface. The orbital parameters are these describing Earth's orbital ecliptic: semi-major axis, eccentricity, obliquity (ϵ), and also perihelion which is a parameter related to Earth's precession (Berger, 1978).

The long-term variation of the obliquity, eccentricity and precession may be calculated through trigonometric expansion. The amplitudes, rates and phases of the expansion are provided by Berger (1978) and these are used in this study. This parametrization is valid for the past and future 1.5 million years.

2.2 Solar Geometry

Solar geometry computations for this model produce solar zenith angle and solar azimuth angle. Computing the solar geometry requires calculations of solar declination (δ) and solar hour angle for each instant. The solar declination is computed as:

$$\delta = \sin^{-1} \sin \epsilon \sin \lambda_{ts} \tag{1}$$

where (λ_{ts}) is the longitude of the true Sun.

Computing the solar hour angle requires correction of the mean solar time to true solar time through the Equation of Time. Corrections are also applied to both the solar zenith angle and solar azimuth angle. The solar zenith angle is corrected for parallax and atmospheric refraction, while the solar azimuth angle is corrected for grid convergence.

2.3 Atmospheric attenuation

As the solar energy travels through the atmosphere it is attenuated by scattering and absorption of atmospheric constituents. Atmospheric extinction is wavelength-dependent (λ) and the direct irradiance ($E_b^n(\lambda)$ [W m^{-1} µm^{-1}]) received at a surface normal to the Sun is (Gueymard, 2005):

$$E_b^n(\lambda) = E^0(\lambda)\boldsymbol{T}^{\downarrow}(\lambda) \quad (2)$$

where $E^0(\lambda)$ is the top of the atmosphere irradiance that is corrected for Earth-Sun distance, and $\boldsymbol{T}^{\downarrow}(\lambda)$ is the total transmissivity which is the product of the tranmsissivity coefficients from various extinction processes.

In this study attenuation due to Rayleigh scattering, ozone absorption, water vapor absorption, and aerosol extinction is considered. Rayleigh, ozone, and water vapour transmittance are calculated as parameterized by Gueymard (2005). For aerosol transmittance the Ångstrøm turbidity formula was used (Ångstrøm, 1930; Iqbal, 1983).

2.4 Direct irradiance

The exoatmospheric solar radiation that is provided by irradiance standards has to be corrected for variation in Earth-Sun distance using the eccentricity correction factor (F_{ec}). The direct surface irradiance on a normal to the Sun surface is related to the top of the atmosphere irradiance though the total transmissivity. The solar irradiance also has to be corrected for the Sun's position relative to the location on Earth that is of interest.

Direct irradiance on a horizontal surface is a function of the Sun's zenith angle; however, if the surface is not horizontal but tilted, direct irradiance ($E_b(\lambda)$) is a function of the incidence angle ($\cos\theta_i$), which is the angle between the Earth-Sun vector and the normal to the surface. In this study, cast shadow (S) on subpixel level is also considered, where S is 1 if there is no cast shadow and 0 if there is a cast shadow. Finally, the direct irradiance is computed as:

$$E_b(\lambda) = E^0(\lambda)F_{ec}\boldsymbol{T}^{\downarrow}(\lambda)S\cos\theta_i \quad (2)$$

2.5 Diffuse irradiance

The diffuse irradiance on a horizontal surface may be divided into Rayleigh-scattered diffuse irradiance, aerosol-scattered diffuse irradiance and diffuse irradiance that has been scattered multiple times between ground and sky. The diffuse irradiance on an inclined unobstructed surface is calculated as a function of solar and terrain geometry. To account for the obstruction of the sky by the terrain, the total diffuse irradiance on an inclined unobstructed surface is multiplied by the hemispherical skyview factor which is an approach for automated multi-scale detection of topographic shielding.

3. Model Evaluation

Simulation results are validated against in-situ measurements and are also compared to solar radiation station data provided by National Renewable Energy Laboratory (NREL) Solar Radiation Database 1991-2010. Global, direct and diffuse radiation measurements are available for a number of stations across the Unites States. Additionally, the developed solar radiation model is compared to the solar radiation models in GRASS and ArcGIS.

3.1 Preliminary Evaluation of Direct Irradiance

Comparison of the direct irradiance component of the solar radiation model was performed on a 75 km by 75 km area over the Nanga Parbat Massif, Pakistan. Simulations of direct irradiance were performed for August 15, 2013 using the developed solar radiation model (TAMU), the solar radiation model available in GRASS, and the one available in ArcGIS (fig. 2 and table 1). The results exhibit a high-degree of multi-collinearity due to local topographic effects.

Model comparison showed that the Root Mean Square Error (RMSE) is 1082.2 Wm^{-1} for TAMU vs. GRASS, 744.1 Wm^{-1} for TAMU vs. ArcGIS, and 1,808.1 Wm^{-1} for ArcGIS vs. GRASS. Difference between the integrated daily simulation shows that the TAMU model underestimates the direct solar irradiance as compared to GRASS, but overestimates as compared to ArcGIS.

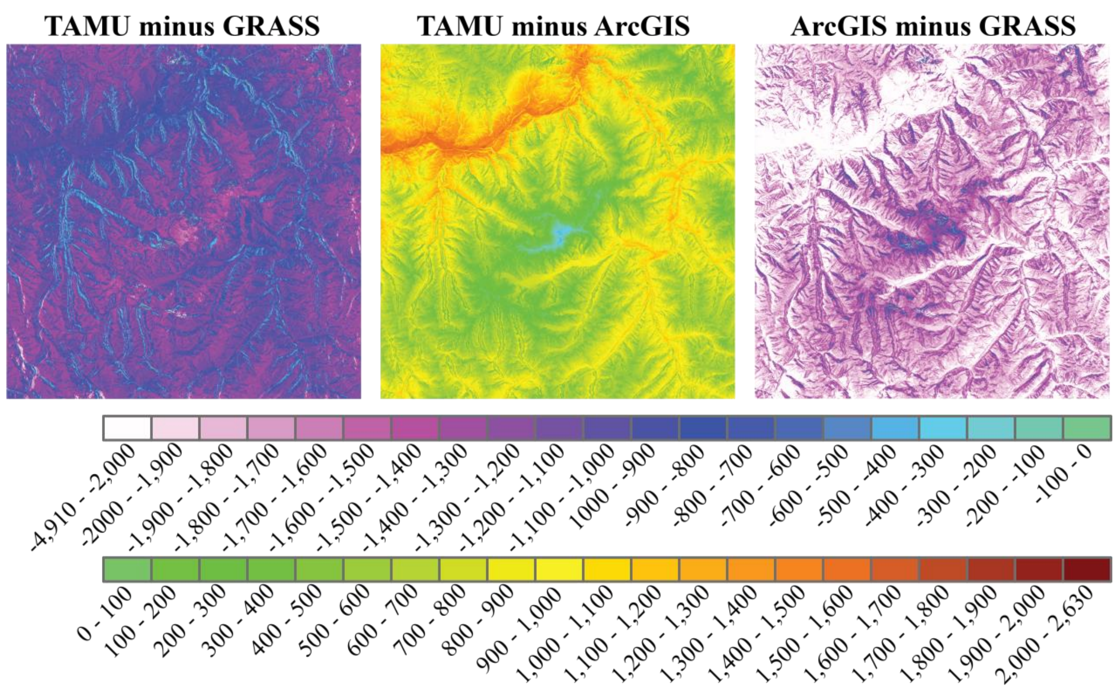

Figure 2. Difference between daily integrated direct irradiance for the different model comparisons (units of W m-1 day-1).

	Maximum	Minimum	Mean	St. deviation
TAMU	7,051.3	0	5,359	927.2
GRASS	8,766.5	0	6,436.3	1,061.3
ArcGIS	7,602.8	0	4,647.5	892.7

Table 1: Statistics for integrated daily direct solar irradiance.

4. Parallelization

The object-oriented framework of the model was found to be a limitation in terms of parallelization as the NVIDIA GK104 GPU was not capable of handling C++ objects. As a result, initial parallelization efforts focused on exploring the speed up potential of parallelizing the spectral processing of the solar radiation model. The parallelized code to accomplish spectral processing instead of spatial grid-cell-based processing gained nearly 90x speed up, and the system performance bottleneck was shifted from computing to the CPU-GPU PCIe bus.

5 Conclusions

The new solar radiation model better represents irradiance over complex topography which permits us to examine the complexities of mountain geodynamics and multi-scale topographic effects over longer time periods. As the complexity of the solar radiation model increased due to simulation accuracy enhancements, its computation complexity, both in terms of different arithmetic computations and the required computing cycles, also increased. We are exploring parallelization techniques to speed up the computing time of the model, on both current and future generations of fine grained parallel architectures.

5. References

Ångstrøm, A., 1930. On the Atmospheric transmission of Sun radiation. *Geografiska Annaler*, 130–159.

Berger, A. L., 1978. Long-term variations of daily insolation and Quaternary climatic changes. *Journal of the Atmospheric Sciences* 35 (12).

Iqbal,M., 1983. *Introduction to Solar Radiation*. Academic Press. New York – London

Gueymard, C., 2005. *SMARTS2, a simple model of the atmospheric radiative transfer of sunshine: Algorithms and performance assessment*. Tech. Rep. FSEC-PF-270-95, Florida Solar Energy Center.