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MODELLING AND VALIDATION OF THE POTENTIAL SOLAR RADIATION FOR THE HORNSUND REGION – APPLICATION OF THE R.SUN MODEL

MODELOWANIE DOPŁYWU POTENCJALNEGO PROMIENIOWANIA SŁONECZNEGO DLA OBSZARU HORNSUNDU I WERYFIKACJA WYNIKÓW – ZASTOSOWANIE R.SUN

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Introduction

The spatial and temporal variations of incoming solar energy determine the dynamics of many landscape processes, including snow and ice melt, thaw/freeze cycles, air and soil temperature and moisture, photosynthesis and evapotranspiration, all with a strong impact on the local climate diversity. Accurate, both in space and time, solar radiation data are needed for many applications and can be very useful in polar climatology, supporting studies of the dynamics of glaciated and nonglaciated ecosystems and their behavior under climate change scenarios.

Solar radiation reaching the Earth's surface is a result of complex interactions of energy between the atmosphere and surface. At a global scale, the latitudinal gradients of radiation are caused by the geometry of the Earth and its rotation and orbit around the Sun. At regional and local scales, terrain (relief) is the major factor modifying the spatial distribution of radiation. Variability in elevation, surface inclination (slope), orientation (aspect) and shadows cast by terrain features may create strong local gradients in incoming solar radiation.

To account for the spatial variation of solar radiation in mountainous areas, solar radiation models integrated within the Geographical Information Systems (GIS) and considering slope, aspect and shadowing effects, are useful. In fact the integrated GIS-solar models, with strong theoretical background of astronomical and atmospheric information, together with terrain characteristics, are the only solution for small but heterogeneous regions with a lack of observational data, that limits the applicability of other methods (e.g. spatial interpolation). Solar models available through GIS systems have been developed since 1990s. The first models were based on simple empirical formulae, e.g. SolarFlux for ArcInfo (Dubayah and Rich, 1995), Solei for Idrisi (Miklánek, 1993) and Genasys (Kumar et al., 1997). More advanced solutions are implemented in Solar Analyst, which is an extension of ArcGIS (Fu and Rich, 2000) and the SRAD model (McKenney et al., 1999), both designed and suitable for fine scale analysis.

The r.sun model, which has been used in our study, is based on the previous work by Hofierka (1997), and is available as a part of the OpenSource GIS GRASS environment (GRASS Development Team, 2007; Hofierka and Šuri, 2002; Šuri and Hofierka, 2004). This model was used to prepare the data for the European Solar Radiation Atlas project of the European Commission (Scharmer and Greif, 2000).

This paper brings the general concept of the r.sun model and presents the preliminary results of beam and diffused solar radiation for the for the surroundings of the Polish Polar Station in Hornsund Fjord, SW Spitsbergen. The calculated spatial patterns of solar radiation are presented for different time periods and validated by comparison with the measurements. The study is performed as part of the TOPOCLIM project, under the 4th International Polar Year activities.

The r.sun model

The r.sun model is designed to calculate the irradiance/irradiation for both clear-sky and overcast conditions. The model works in two modes. In the first mode, raster maps of instantaneous beam *(I_B)*, diffuse *(I_D)* and reflected solar irradiance [Wm^{-2}], together with the solar incident angle [degrees] can be calculated for a given day and time. In the second mode the spatial patterns of daily sums of solar irradiation [Whm^{-2}] and duration of the beam irradiation [minutes] are computed. The model requires only a few mandatory input parameters: elevation above the sea level; slope and aspect of the terrain; local solar time (for mode 1); and a day number (for both modes). The user may also change the default setting of other parameters, including the Linke atmospheric turbidity factor *(L_{TF})*, ground albedo and real sky radiation coefficients separately for beam and diffuse components. Spatially distributed parameters can be set as raster maps. Optionally, the model accounts for obstructions of the sky by local terrain features from the Digital Elevation Model (DEM). The astronomical parameters, such as solar declination, are computed internally by the model.

The starting point for the beam component irradiation modelling is the solar constant, which is then corrected for the Earth's orbit eccentricity (day number) and the attenuation by a cloudless atmosphere using the Linke atmospheric turbidity factor and Rayleigh optical thickness at a given air mass. After this, the beam irradiance fo a horizontal surface and then an inclined surface [Wm^{-2}] are calculated.

The modelling of the diffuse component for a horizontal surface [Wm^{-2}] is a product of the normal extraterrestrial irradiance, a diffuse transmission function dependent on the L_{TF}, and a diffuse solar altitude function dependent on the solar altitude. The Linke turbidity factor is a key component as atmospheric turbidity increases the diffuse radiation and decreases the direct radiation.

The Linke turbidity factor is a key element influencing the modelled results for both beam and diffused radiation. It expresses the absorption by the water vapor and the absorption and scattering by the aerosol particles and can be interpreted as the number of clean dry atmospheres that would be necessary to produce the same attenuation of the extraterrestrial radiation that is produced by the real atmosphere (Louche et al., 1986). In this way, it compares the actual atmospheric extinction coefficient of the atmosphere over the whole solar spectrum with the theoretical atmospheric extinction coefficient of pure dry air over the same spectrum and path length (Vida et al., 1999). The larger the L_{TF}, the stronger is the attenuation of the radiation by the clear sky atmosphere.

The estimation of the clear-sky ground reflected irradiance for inclined surfaces and computation of overcast irradiation has not been performed in this study. The detailed description of the procedure can be found in Hofierka and Šuri (2002) or Šuri and Hofierka (2004).

The r.sun model can be used, as mentioned above, to calculate instantaneous or daily radiation. The model output may be aggregated to other time spans. This can be easily done, for example, using Linux shell scripts. In this paper, monthly, daily and instantaneous spatial patterns of beam and diffused and total (beam+diffused) radiation are presented, whereas the model validation is based on measured data.

Study area

The study area is the locality of the Werenskjold Glacier in SW Spitsbergen (Wedel Jarlsberg Land), with a special attention for the Arie Valley in the vicinity of the Polish Polar Station in the Hornsund Fjord (Fig. 1). The whole area covers 288 km^2; the elevation changes from sea level to 948 m a.s.l. and the steepest slopes reach 68 degrees.

Input data

The following mandatory spatial input data were provided as an input to the r.sun model:

1. 10-meter resolution digital elevation model (DEM; Fig. 1) based on the source data for the orthophotomap (1:25 000) „Werenskioldbreen and surrounding areas" (© Norsk Polarinstitutt and Silesian University).
2. Inclination and orientation of terrain calculated using the r.slope.aspect GRASS function to process the DEM.
3. The Linke Turbidity factor is assumed to be spatially constant over the study area, but due to the dynamic temporal nature, the calculations are performed for each hour of the year using the real solar elevation to avoid a certain degree of generalisation. The L_{TF} is calculated with the formula proposed by Dogniaux (1984), fide Page (1986):

$$L_{TF} = \left(\frac{85+\gamma}{39.5\exp(-w)+47.4} + 0.1 \right)(16+0.22w)\beta_A$$

where γ is the solar elevation in degrees, w is the precipitable water vapour contents (PWC) in [cm] and β_A is the Angstrom turbidity coefficient (dimensionless). In the absence of available observational data for w and β_A, according to Dogniaux, the following values were used: 2 cm of precipitable water content and β_A = 0.05. The constant PWC value over the year is a simplification, as it is expected to change, for example, with air temperature.

Model validation

Instantaneous total radiation measurements are available from the Polish Polar Station for the years 2005 and 2006, together with cloud cover data (in 3-hourly steps). As the clear-sky radiation is the point of interest in this paper, periods with cloudiness less or equal to one (in octants) are selected and compared with the modelled total radiation. The number of clear-sky total radiation measurements is 158.

Results & discussion

Monthly average beam, diffused and total (beam+diffused) solar radiation, calculated from the modelled daily radiation sums, is presented in Figure 2. The largest spatial variations are for the beam radiation and are related to the complex terrain and, therefore, variations in slope and aspect. The steep south facing slopes receive much larger amounts of beam solar radiation than the slopes of northern exposure. In August, there are small areas with no direct radiation, i.e. permanently shadowed by the surrounding mountain ridges. The spatial variations of diffused radiation are not large, and the spatial pattern of the total solar radiation is similar to that calculated for the beam radiation.

Daily beam radiation is presented for selected days of the period from 1st of May to 1st of September (Fig. 3). The shadowing effects of the surrounding mountains are clearly pronounced at the beginning of May, on 15th August and in September.

Instantaneous beam radiation for the selected area is presented at 3 hourly steps, starting on 15th of August, at 00 local solar time (Fig. 4). The modelled beam solar radiation for the selected area changes from 0 to almost 1000 Wm^{-2}. The location of the shadowed areas changes during the day, but each time their spatial extent is substantial. This might have significant influence on various aspects of the environment. The mean air temperature of August is within the range of +4.4 to +5.2°C, therefore large variations in incoming solar radiation over the day may lead to frequent freeze / thaw cycles and may influence the hydrological cycle, etc.

The r.sun model results are compared with the measured total (beam+diffused) solar radiation values (Fig. 5). There is a good agreement between the modelled and measured total radiation despite the relatively simple meteorological parameterization. The adjusted R^2 is above 0.93, with the mean absolute error close to 35 W. It should, however, be noticed that the r.sun model tends to overestimate the modelled total radiation for the values larger than 400 Wm^{-2}. This may be attributed to the simple parameterization of the L_{TF} factor, which is calculated with the PWC being constant over the year. For the warm season, the PWC is expected to be higher, and this can explain the differences between the modelled and measured results.

Summary

The preliminary results of clear-sky radiation modelled with r.sun are presented and checked against the available measurements. The model is found to be in good agreement with the measurements, despite its simple meteorological parameterization. Improvements in the L_{TF} calculation are needed and preferably based on the measurements. This will probably increase the overall agreement between the modelled and observed results for the clear sky conditions.

The r.sun model can be considered as a robust and very flexible GIS tool for radiation modelling. The main strength of the model is its simplicity and relatively small demands on input data. There are no hard-coded limitations, for example, for the area size or it's resolution. High resolution modelling, especially incorporating the shadowing effect of terrain, however,

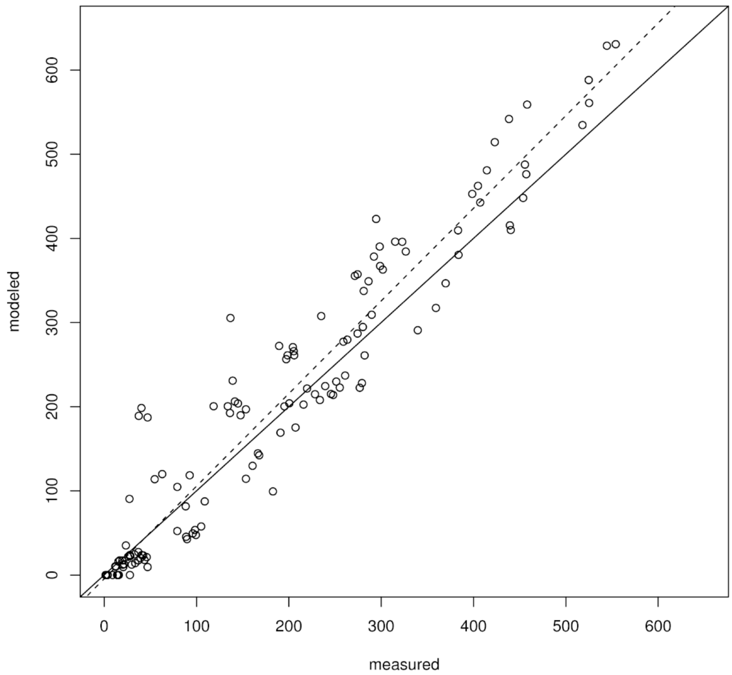

Figure 5. Modelled vs. measured solar radiation [Wm^{-2}]. 1:1 line – solid, best fit line – dashed

can be time and resource consuming. On the other hand, high resolution and quality of the input DEM is of great importance for the final results, especially for mountainous areas.

The results presented here are for the clear-sky conditions, which are not very common in the Spitsbergen area. The r.sun model is also able to calculate the beam and diffused solar radiation for the overcast sky and some preliminary results, not presented here, are encouraging. As these data are valuable for ecological, glaciological or hydrological studies, work will be undertaken to provide the spatial data on radiation under the real sky (including overcast) conditions.

References

Dougniaux R., 1984: De l'influence de l'estimation du facteur total de trouble atmosphérique sur l'évaluation du rayonnement solaire direct par ciel clair. Application aux données radiométriques de L'IRM a´ Uccle. Institut Royal Météorologique de Belgique (IRM), Miscellanea, Ser. C.

Dubayah R., Rich P.M., 1995: Topographic solar radiation models for GIS. *Int J Geogr Inform Syst* 9:405-419

Fu P., Rich P.M., 2000: The Solar Analyst 1.0 user manual. Helios Environmental Modeling Institute, http:/ /www.hemisoft.com.

GRASS Development Team, 2007: Geographic Resources Analysis Support System (GRASS) Software. ITC-irst, Trento, Italy. http://grass.itc.it.

Hofierka J., Šuri M., 2002: The solar radiation model for Open Source GIS: implementation and applications, Proc of the Open Source GIS – GRASS users conference 2002 – Trento, Italy, 11-13 September 2002.

Kumar L., Skidmore A.K., Knowles E., 1997: Modelling topographic variation in solar radiation in a GIS environment. *Int J Geogr Inform Sci* 11(5): 475-497.

Louche A., Peri G., Iqbal M., 1986: An analysis of Linke Turbidity Factor. *Solar Energy* 37(6):393-396.

McKenney D.W., Mackey B.G., Zavitz B.L., 1999: Calibration and sensitivity analysis of a spatially-distributed solar radiation model. *Int J Geogr Inform Sci* 13(1): 49-65.

Miklánek P., 1993: The estimation of energy incom in grid points over the basin using simple digital elevation model. Ann Geophys, European Geophysical Society. Springer, Suppl. II, 11:296.

Page J.K., 1986: Prediction of solar radiation on inclined surfaces. Solar Energy R & D in the European Community, Series F, Solar Radiation Data, vol. 3. Dordrecht: Reidel Publishing Company.

Scharmer K., Greif J. (eds), 2000: The European Solar Radiation Atlas, Volume 2: Database and Exploitation Software. Les Presses de l' École des Mines: Paris. http://www.helioclim.net/esra/index.html.

Šuri M., Hofierka J., 2004: A New GIS-based Solar Radiation Model and Its Application to Photovoltaic Assessments. *Trans GIS* 8(2):175-190.

Vida J., Foyo-Moreno I., Alados-Arboledas L., 1999: Performance validation of MURAC, a cloudless sky radiance model proposal. *Energy* 24:705-721.

Abstract

R.sun is a solar radiation model implemented in the OpenSource GRASS GIS. The model can be used to calculate spatial patterns of both instantaneous and daily sums of beam, diffused and reflected solar radiation. The input data are digital elevation model, needed to calculate slopes and their aspects, and the Linke turbidity factor, which describes the attenuation of the solar radiation in the atmosphere. Optionally, terrain-shadowing effects may be considered, which is important for areas with complex relief. Effects of cloudiness on the incoming solar radiation can also be parameterised, separately for the beam and diffused radiation.

Here the r.sun model is applied to calculate the potential (i.e. for cloudless conditions) solar radiation for the Hornsund area (SW Spitsbergen). The shadowing effect is included, which is of special importance for the area because of the relief complexity and low solar altitudes. The results are shown on a series of maps and compared with measurements. The validation of the model shows a good agreement between the model results and the available measurements.

Streszczenie

R.sun jest narzędziem służącym do modelowania dopływu promieniowania słonecznego do powierzchni ziemi, zaimplementowanym w działającym na licencji OpenSource systemie GIS GRASS. Model może być zastosowany do obliczania zarówno wielkości chwilowych (momentowych), jak i dziennych sum promieniowania bezpośredniego, rozproszonego i odbitego. Wejściowymi informacjami są: cyfrowy model terenu, potrzebny do określenia nachyleń i ekspozycji stoków oraz współczynnik zmętnienia Linkego, opisujący zmniejszenie promieniowania słonecznego w atmosferze. Dodatkowo istnieje możliwość uwzględnienia zachmurzenia nieba, parametryzowanego oddzielnie dla promieniowania bezpośredniego i rozproszonego.

Model r.sun zastosowano tu do obliczenia potencjalnego (niebo bezchmurne) promieniowania dla obszaru Hornsundu (SW Spitsbergen). W opracowaniu uwzględniono efekty zacienienia, związane z urozmaiconą rzeźbą terenu, szczególnie istotne przy niskim położeniu słońca nad horyzontem. Wyniki zaprezentowano na mapach i zweryfikowano poprzez porównanie z danymi pomiarowymi. Walidacja modelu wykazała dużą zgodność między wielkościami estymowanymi za pomocą r.sun a zmierzonymi.

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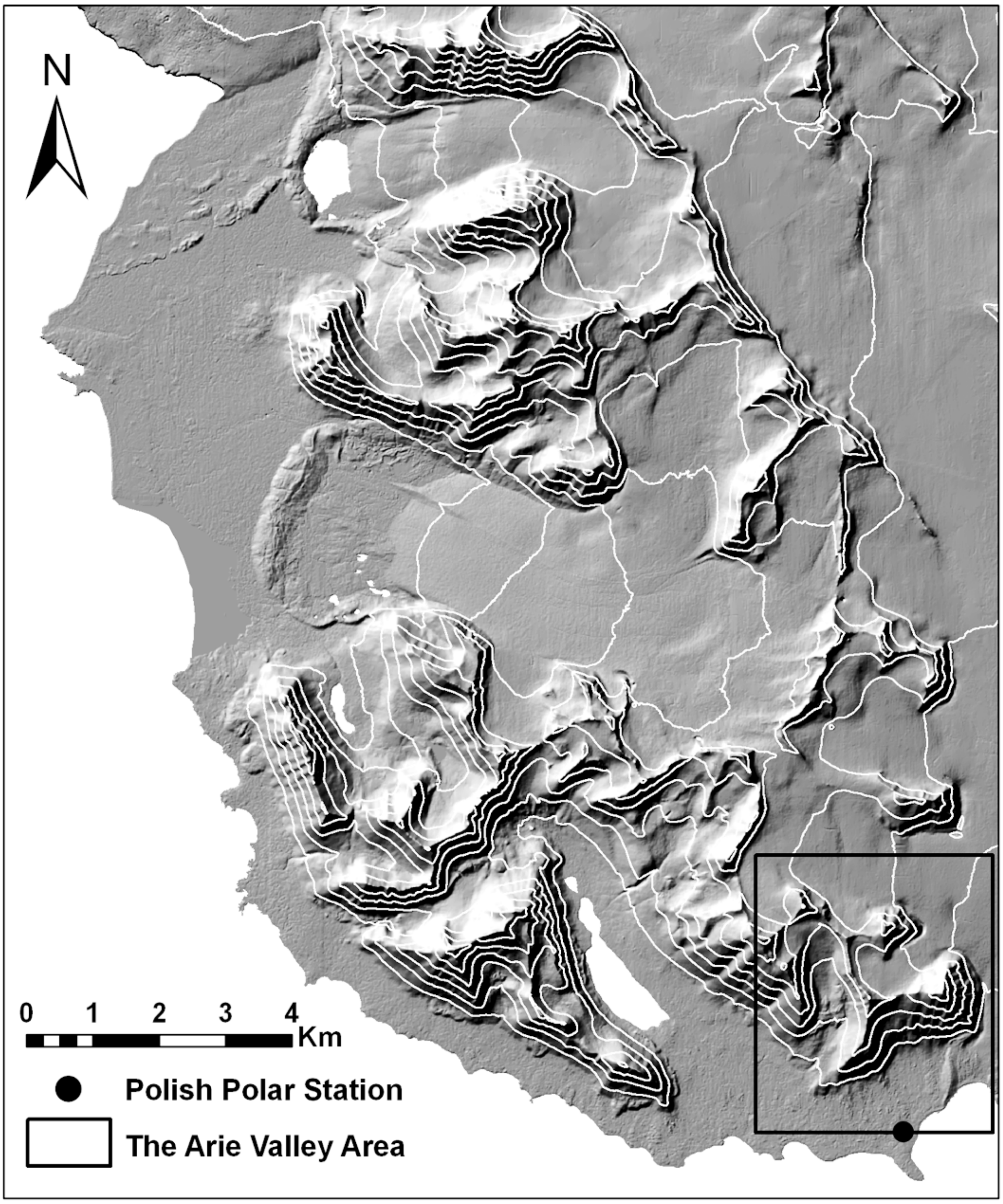

Figure 1. DEM for the study area (contour lines every 100 m)

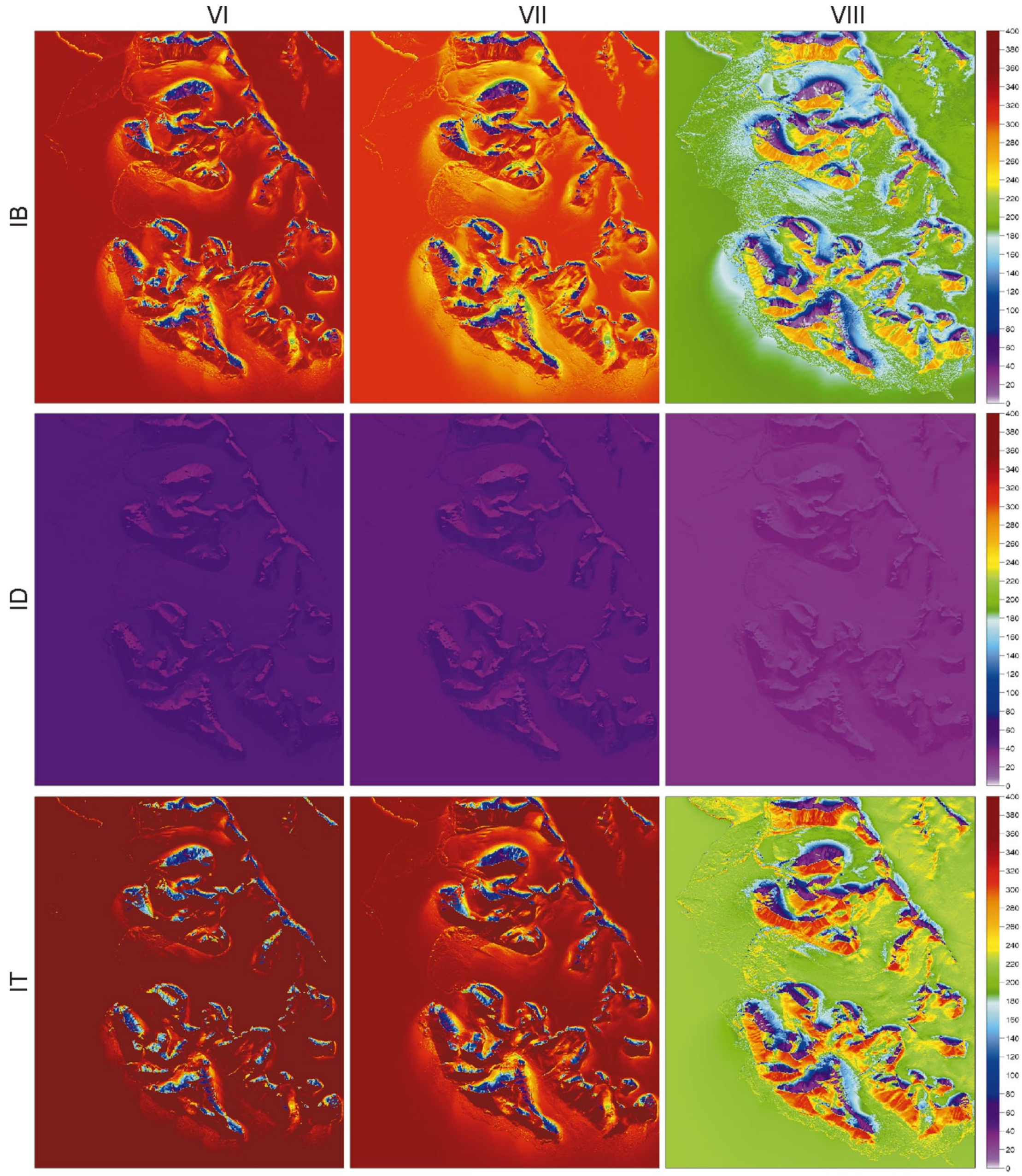

Figure 2. Monthly mean beam (IB), diffused (ID) and total (IT) solar radiation flux under clear sky conditions [Wm^{-2}]

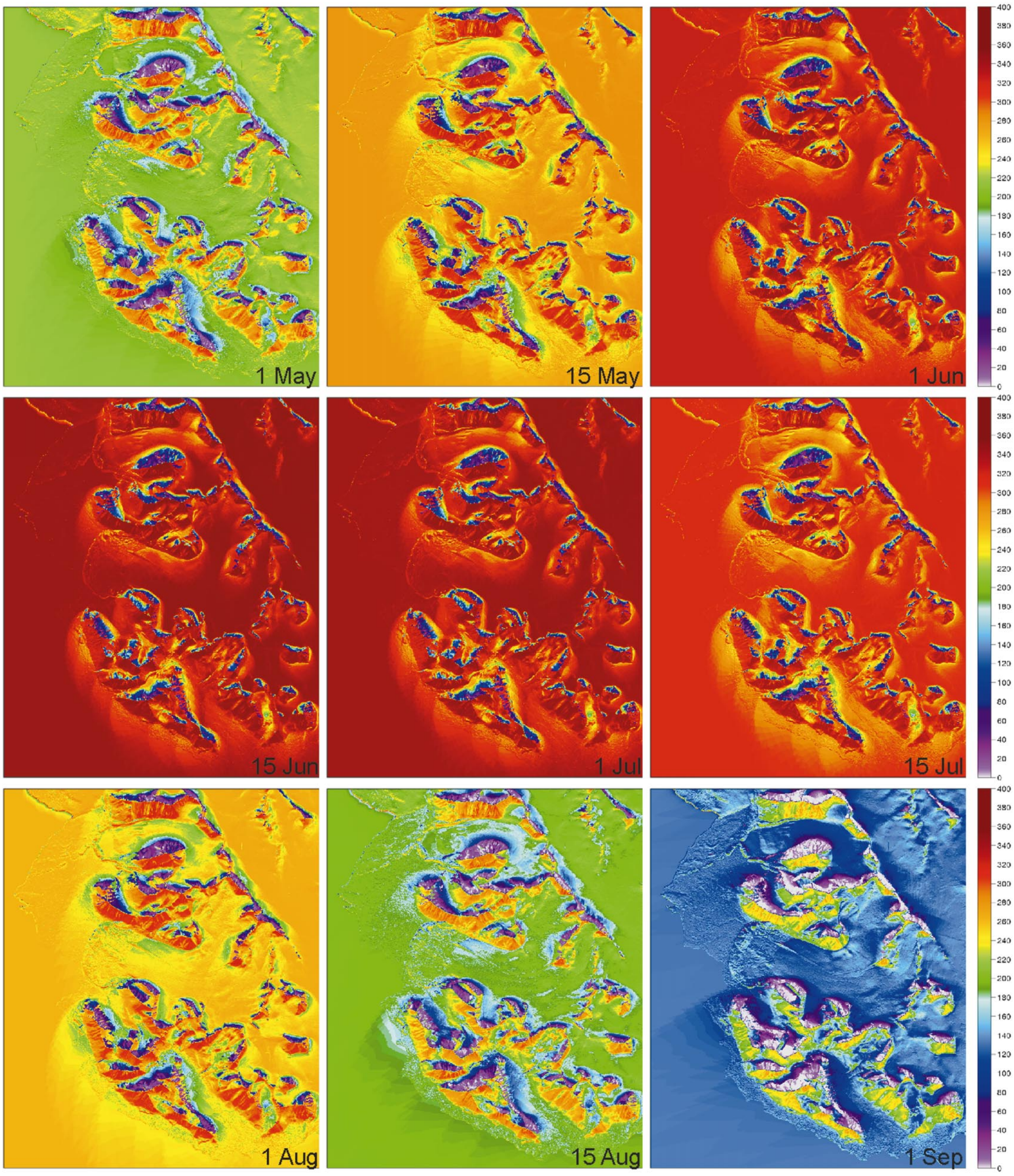

Figure 3. Daily mean beam solar radiation flux under clear sky conditions [Wm^{-2}]

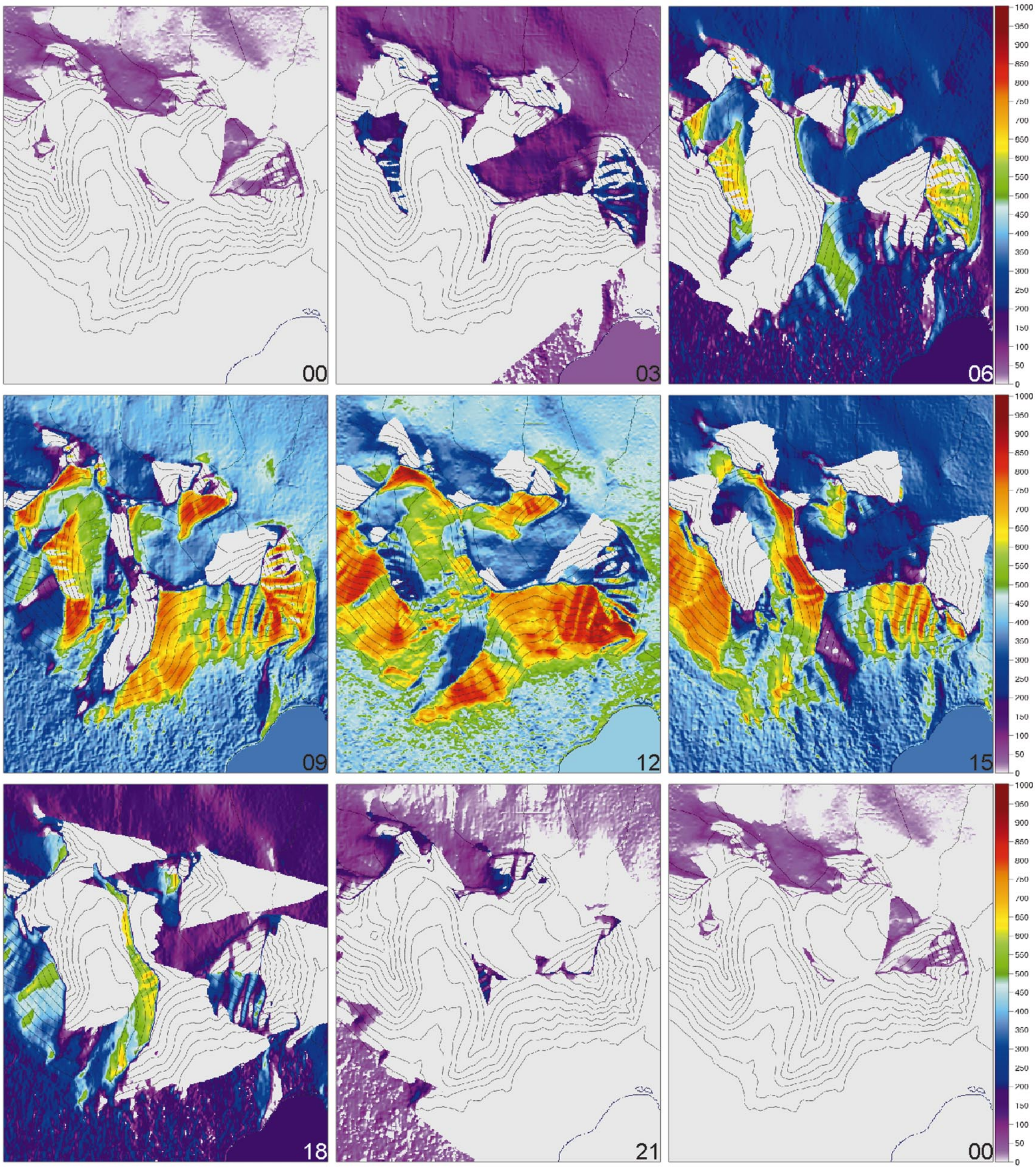

Figure 4. Instantaneous beam solar radiation flux under clear sky conditions [Wm^{-2}, hours in local solar time]