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Adaptive numerical model for solar radiation

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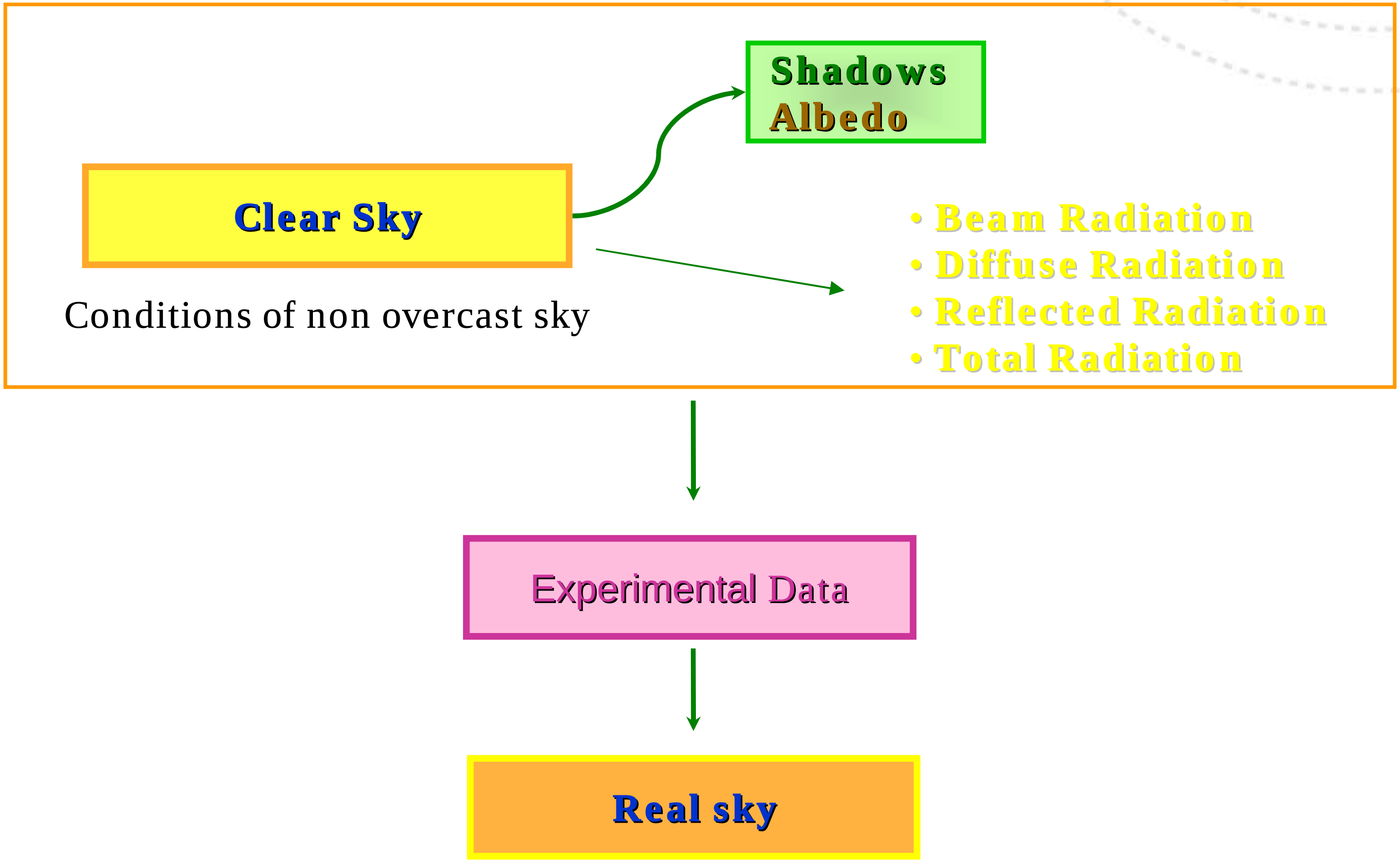
Introduction

- **Solar power is one of the most appreciate renewable energies in the world**

- **Three groups of factors determine the interaction of solar radiation with the earth's atmosphere and surface**
  - a. The Earth's geometry, revolution and rotation (declination, latitude, solar hour angle)
  - b. Terrain (elevation, albedo, surface inclination/orientation, shadows)
  - c. Atmospheric attenuation (scattering, absorption) by
    - c.1. Gases (air molecules, ozone, CO_2 and O_2)
    - c.2. Solid and liquid particles (aerosols, including non-condensed water)
    - c.3. Clouds (condensed water)

- **We focus the study on the accurate definition of the terrain surface and the produced shadows by using an adaptive mesh of triangles**

Introduction



Clear Sky

Conditions of non overcast sky

Shadows
Albedo

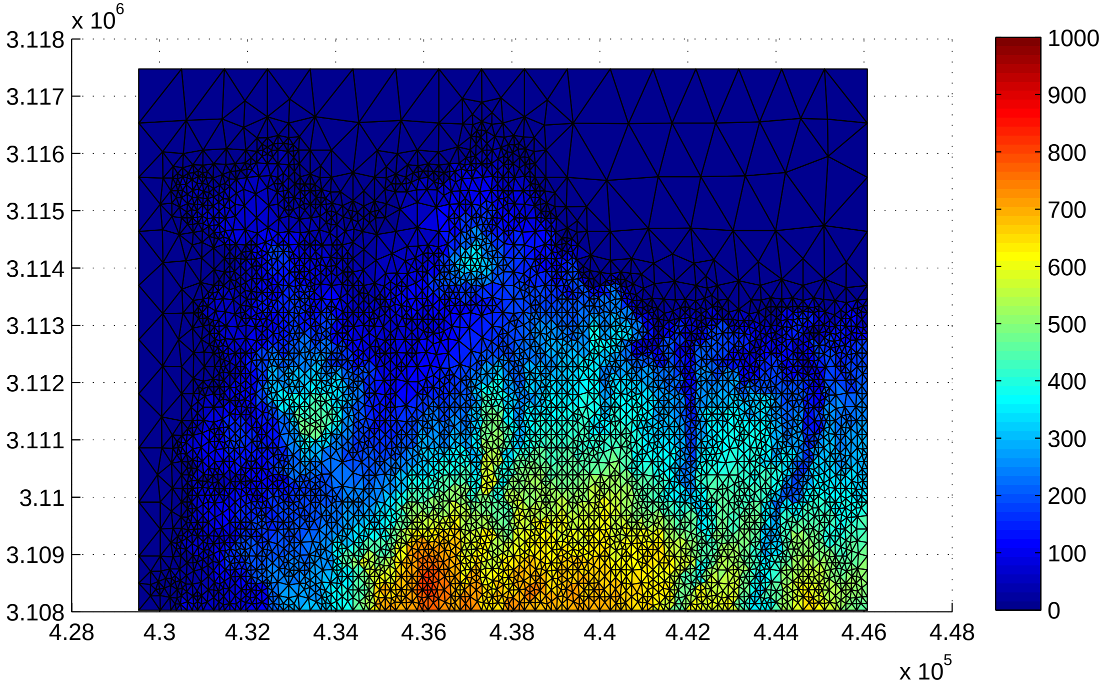
- **Beam Radiation**
- **Diffuse Radiation**
- **Reflected Radiation**
- **Total Radiation**

Experimental Data

Real sky

Construction of the terrain surface mesh

- **Build a sequence of nested meshes from a regular triangulation of the rectangular region, such that the level j is obtained by a global refinement of the previous level j–1 with the 4-T Rivara's algorithm**
- **The number of levels** *m* **of the sequence is determined by the degree of discretization of the terrain,**
- **Define a new sequence until level** $m' \leq m$ **applying a derefinement algorithm.**
- **Two derefinement parameters** ε_h **and** ε_a **are introduced and they determine the accuracy of the approximation to terrain surface and albedo, respectively.**



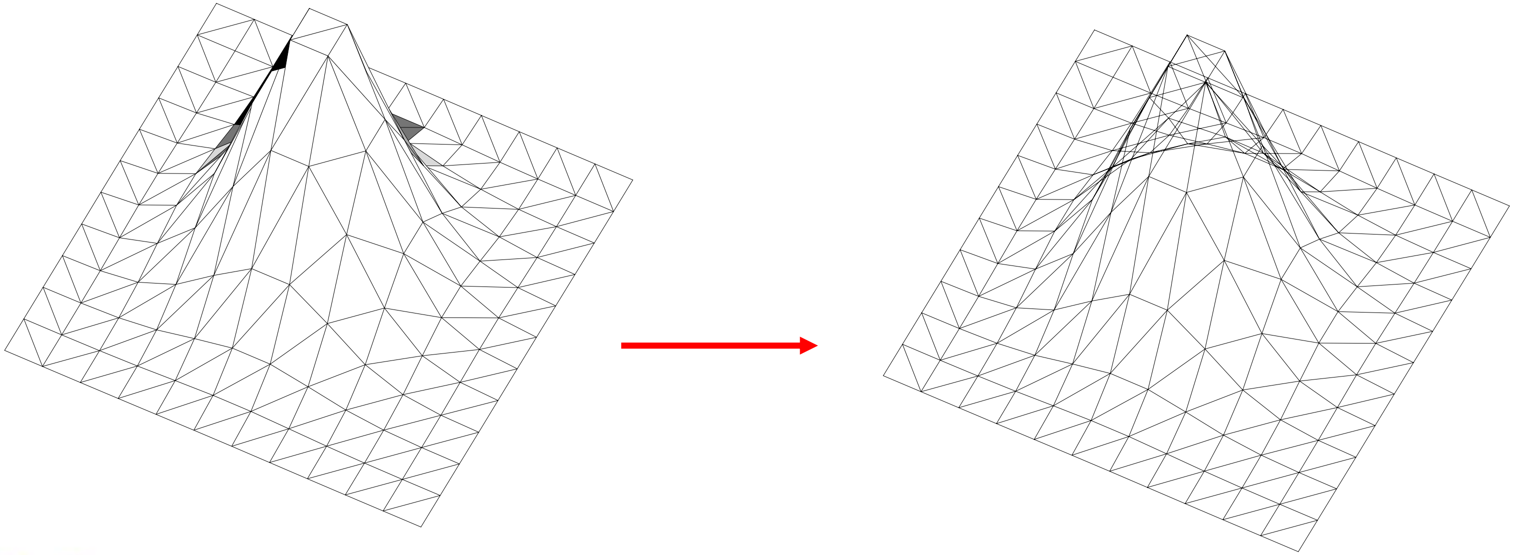
Shadow detection

The solar beam direction is

$$v_{sol} = (\cos h_0 \sin A_0, \cos h_0 \cos A_0, \sin h_0)$$

where h_0 is the solar altitude and A_0, the solar azimuth

Construct a reference system x', y' and z', with z' in the direction of the beam radiation, and the mesh is projected on the plane x'y'



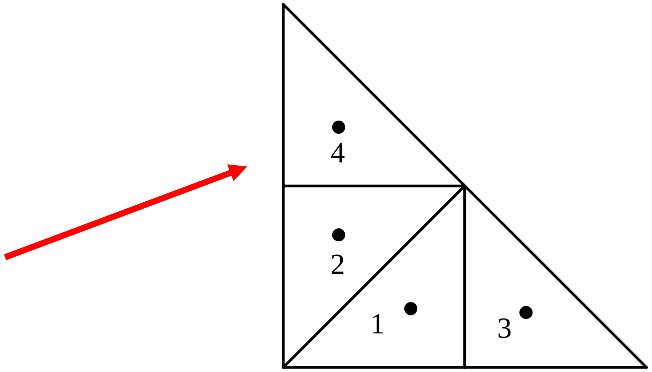
Shadow detection

The incidence solar angle δ_{exp} is then computed for each triangle

Check for each triangle Δ of the mesh, if there exists another Δ' which intersects Δ and is in front of it, i.e., the z' coordinates of the vertices of Δ' are greater than those of Δ.

The analysis of the intersection between triangles involves a high cost.

We have considered four warning points whose area coordinates, referenced to the master element with vertices (0, 0), (1, 0) and (0, 1) are (1/3, 1/6, 1/2), (1/6, 1/3, 1/2), (2/3, 1/6, 1/6) and (1/6, 2/3, 1/6) (the geometrical centres of the 4-T Rivara's subtriangles)

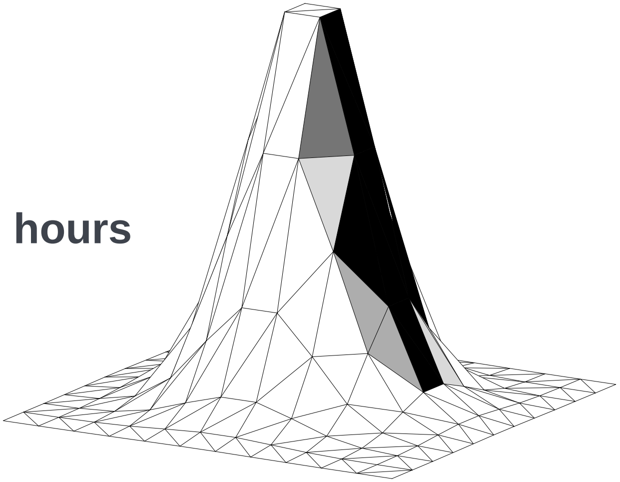


Lighting factor of each triangle

$$Lf = 1 - i/4$$

where i = 0, ..., 4, is the number of warning points inside other triangles that are in front of Δ.

Shadows detection



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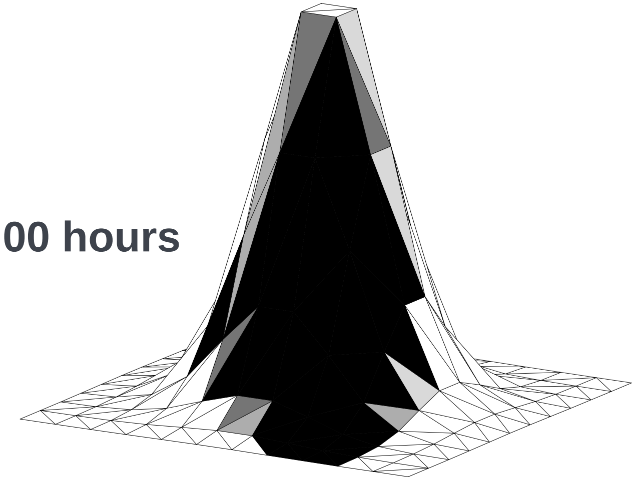

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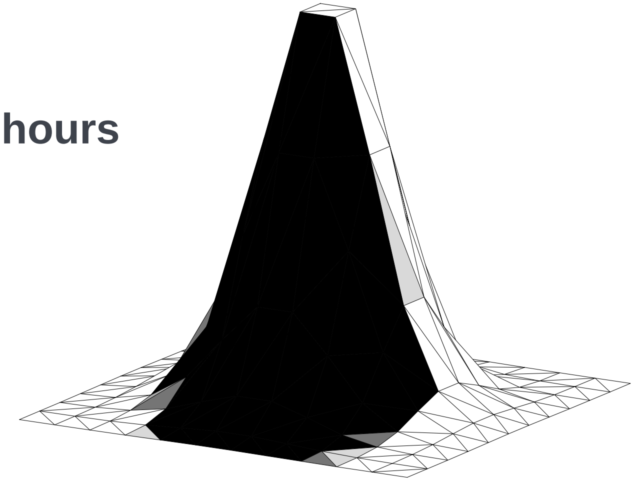

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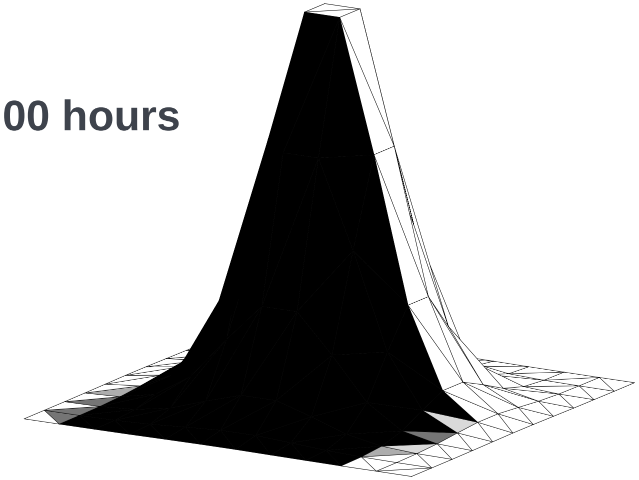

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Solar radiation modelling

General aspects

- This solar radiation model is based on the work of Šúri and Hofierka about a GIS-based model.

- Use of adaptive meshes for surface discretization and a new method for detecting the shadows over each triangle of the surface.

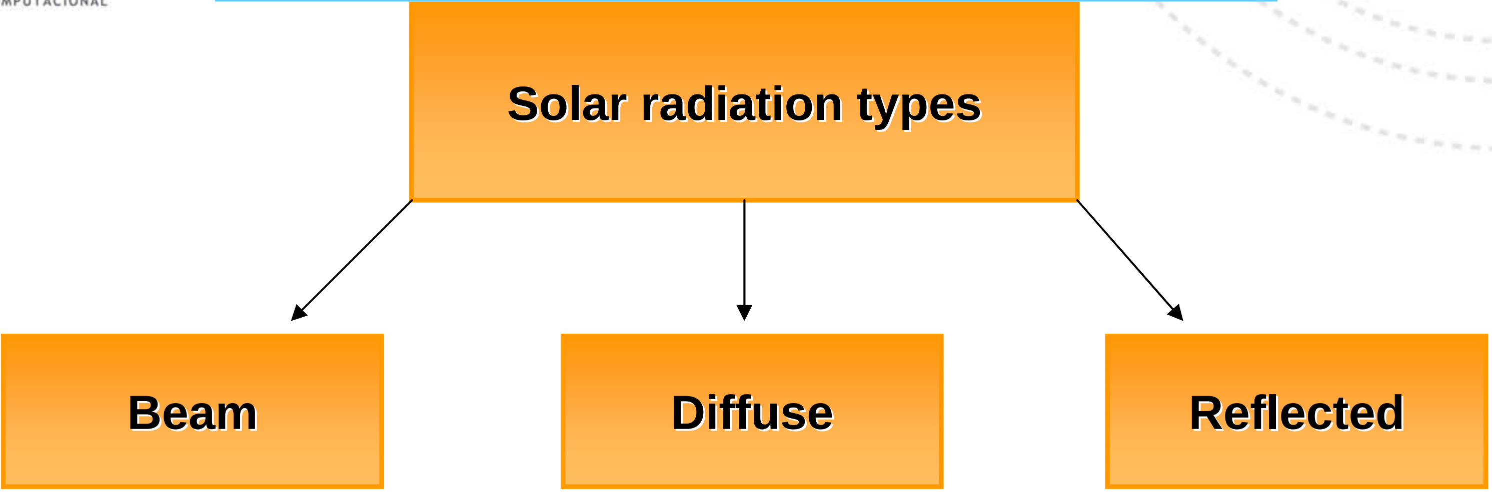
- We first calculate the solar radiation under the assumption of clear sky for all the triangles of the mesh, taking into account the lighting factor of each triangle.

- Next these solar radiation values are corrected for a real sky by using the available data of the measurement stations in each time step along an episode.

- Finally, the total solar radiation is obtained integrating all the instantaneous values in each triangle.

Solar radiation modelling

Solar radiation equations for clear sky

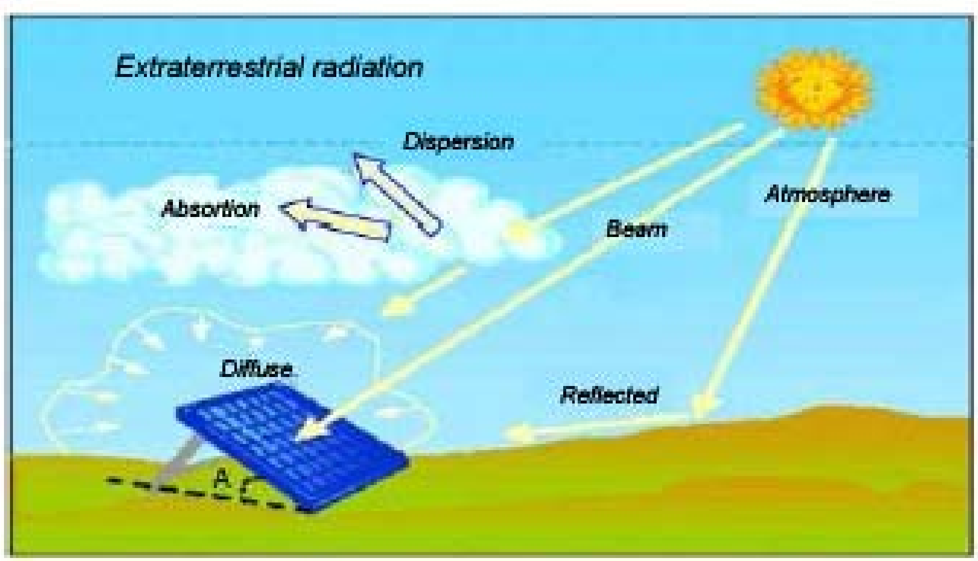


Solar radiation types

Beam

Diffuse

Reflected



Solar radiation modelling

Solar radiation equations for clear sky

Beam radiation

Extraterrestrial irradiance G_0 normal to the solar beam,

$$G_0 = I_0 \epsilon$$

Beam irradiance

Correction factor

$$\epsilon = 1 + 0.03344 \cos(j' - 0.048869)$$

Beam irradiance normal to the solar beam B_{0c}

$$B_{0c} = G_0\, exp\{-0.8662 T_{LK} m \delta_R(m)\}$$

Linke atmospheric turbidity factor

relative optical air mass

Beam irradiance on a horizontal surface

$$B_{hc} = B_{0c} L_f\, sin h_0$$

h_0 is the solar altitude angle
L_f is the lighting factor

Beam irradiance on an inclined surface

$$B_{ic} = B_{0c} L_f \sin \delta_{exp}$$

δ_{exp} the incidence solar angle

Solar radiation modelling

Solar radiation equations for clear sky

Diffuse radiation

Diffuse radiation on horizontal surfaces

$$D_{hc} = G_0 T_n(T_{LK}) F_d(h_0)$$

Diffuse transmission

Function depending on the solar altitude

Diffuse radiation on inclined surfaces

Sunlit surfaces

$h_o \geq 0.1$

$$D_{ic} = D_{hc}\left(F(\gamma_N)(1-K_b) + K_b \frac{\sin\delta_{exp}}{\sin h_o}\right)$$

$h_o < 0.1$

$$D_{ic} = D_{hc}[F(\gamma_N)(1-K_b) + (K_b \sin\gamma_N \cos A_{LN})/(0.1 - 0.008h_o)]$$

$$\boxed{K_b = B_{hc}/G_{oh}}$$

$$\boxed{G_{oh} = G_o \sin h_o}$$

Shadowed surfaces

$$D_{ic} = D_{hc} F(\gamma_N)$$

Solar radiation modelling

Solar radiation equations for clear sky

Reflected radiation

$$R_i = \rho_g G_{hc} r_g(\gamma_N)$$

Mean ground albedo

where

$$r_g(\gamma_N) = (1 - \cos\gamma_N)/2$$

$$G_{hc} = B_{hc} + D_{hc}$$

Solar radiation modelling

Solar radiation under overcast sky

The values of global irradiation on a horizontal surface for overcast conditions G_h are calculated as a correction of those of clear sky G_{hc} with the clear sky index k_c

$$G_h = G_{hc} k_c$$

If some measures of global radiation G_{hs} are available at different measurement stations, the value of the clear sky index at those points may be computed as

$$k_c = G_{hs} / G_{hc}$$

Then k_c may be interpolated in the whole studied zone.

$$k_c = \varepsilon \frac{\sum_{n=1}^{N} \frac{k_{cn}}{d_n^2}}{\sum_{n=1}^{N} \frac{1}{d_n^2}} + (1-\varepsilon) \frac{\sum_{n=1}^{N} \frac{k_{cn}}{|\Delta h_n|}}{\sum_{n=1}^{N} \frac{1}{|\Delta h_n|}}$$

Numerical experiments

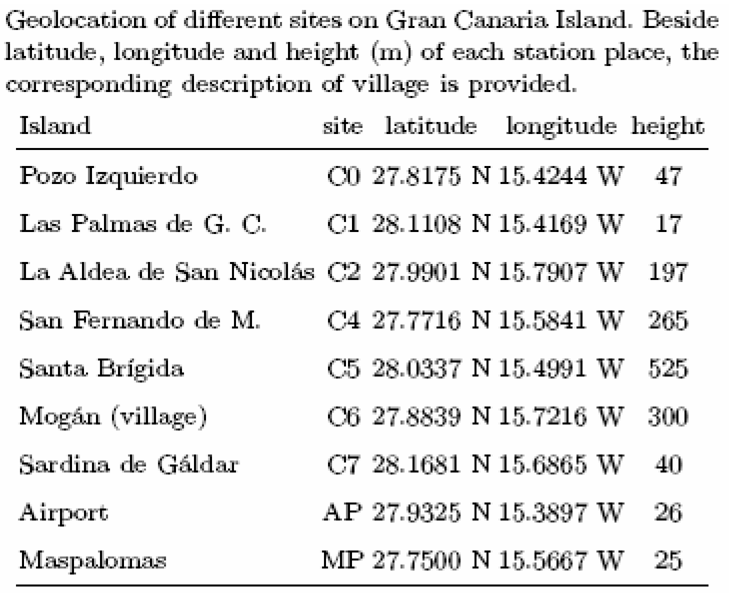
The studied case corresponds to Gran Canaria, one of the Canary Islands in the Atlantic Ocean at 28.06 latitude and –15.25 longitude.
The UTM coordinates (metres) that define the corners of the considered rectangular domain including the island are (417025, 3061825) and (466475, 3117475), respectively.

The selected episode includes the period from September 1st, 2006, until May 31th, 2007

The average overcast global radiation, considering the 273 days with observational data, was 16.8264MJ per day.

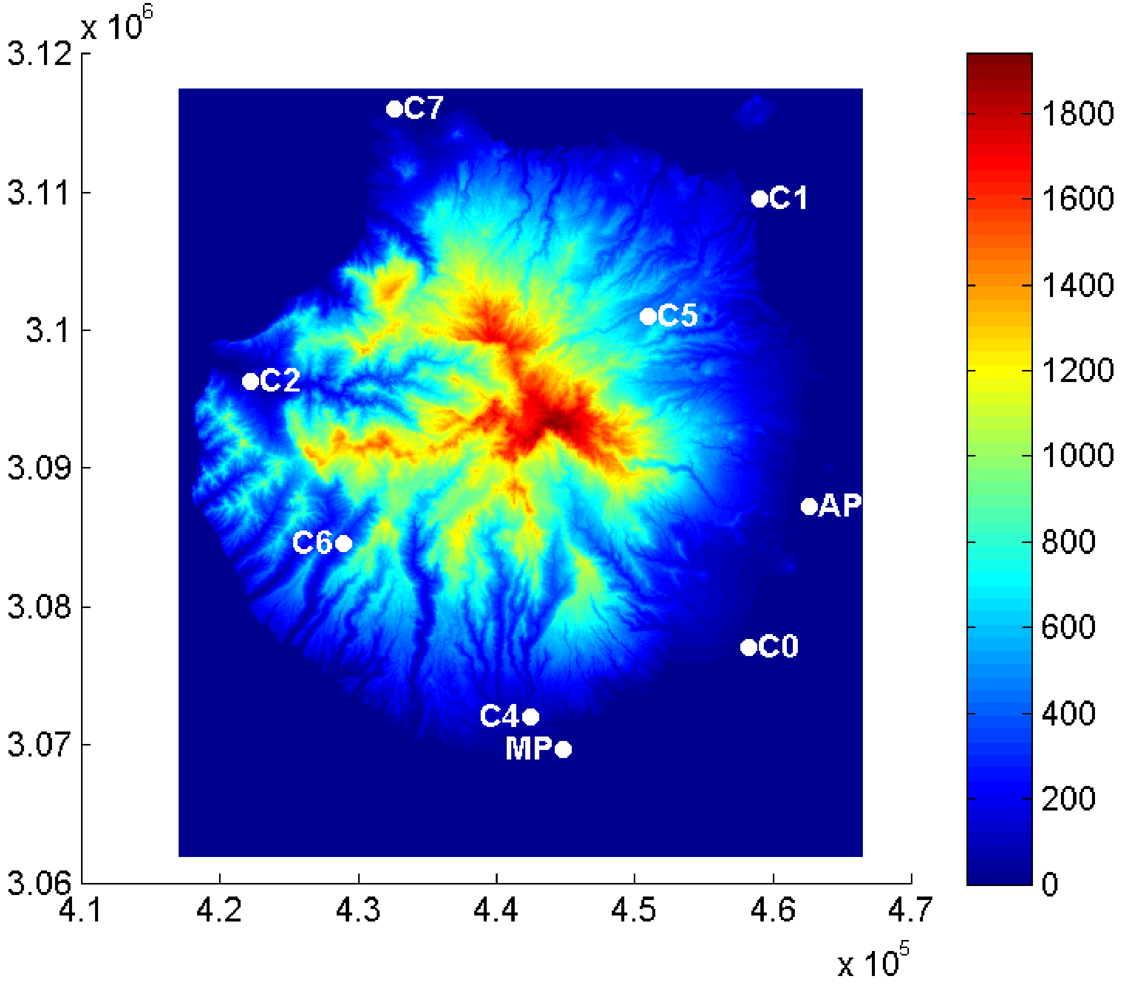
We present the graphical results of December as example.

Numerical experiments



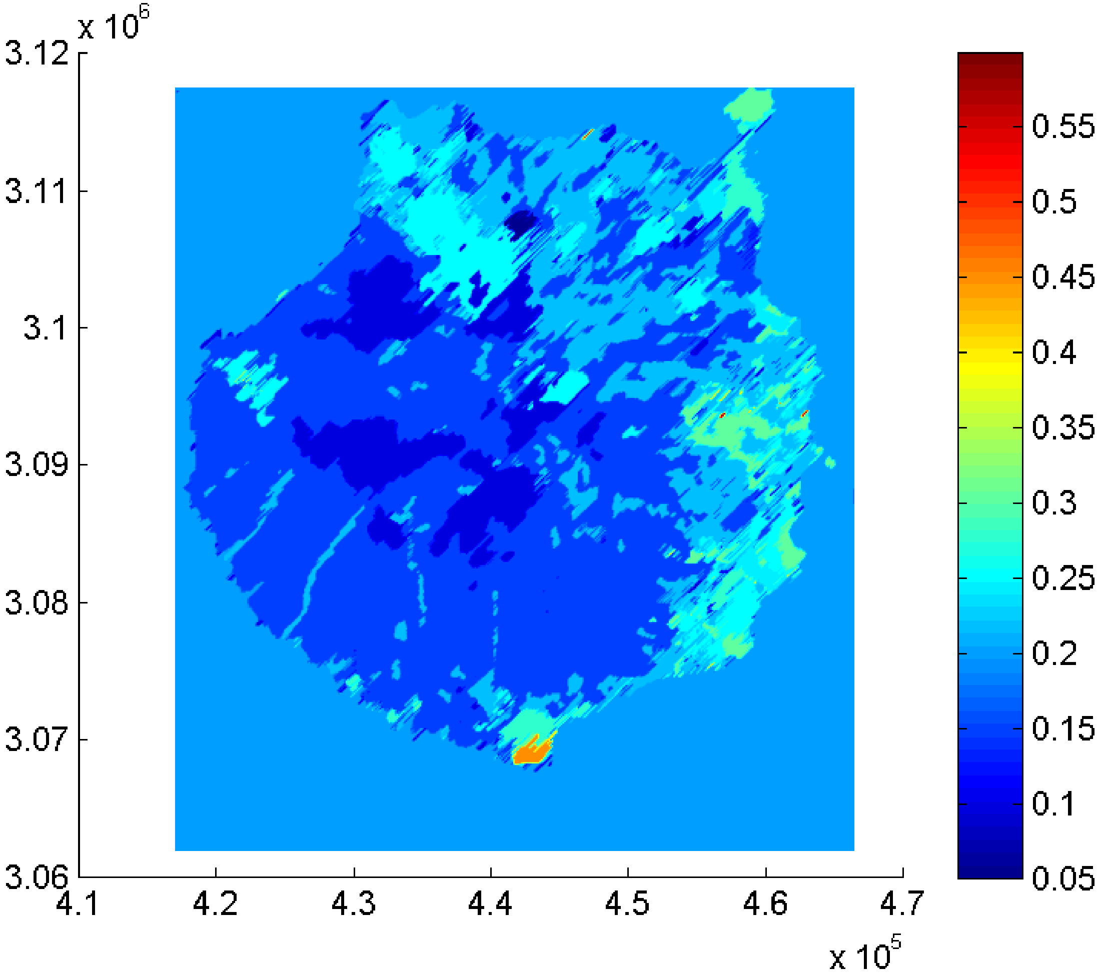
Geolocation of different sites on Gran Canaria Island. Beside latitude, longitude and height (m) of each station place, the corresponding description of village is provided.

Island	site	latitude	longitude	height
Pozo Izquierdo	C0	27.8175 N	15.4244 W	47
Las Palmas de G. C.	C1	28.1108 N	15.4169 W	17
La Aldea de San Nicolás	C2	27.9901 N	15.7907 W	197
San Fernando de M.	C4	27.7716 N	15.5841 W	265
Santa Brígida	C5	28.0337 N	15.4991 W	525
Mogán (village)	C6	27.8839 N	15.7216 W	300
Sardina de Gáldar	C7	28.1681 N	15.6865 W	40
Airport	AP	27.9325 N	15.3897 W	26
Maspalomas	MP	27.7500 N	15.5667 W	25



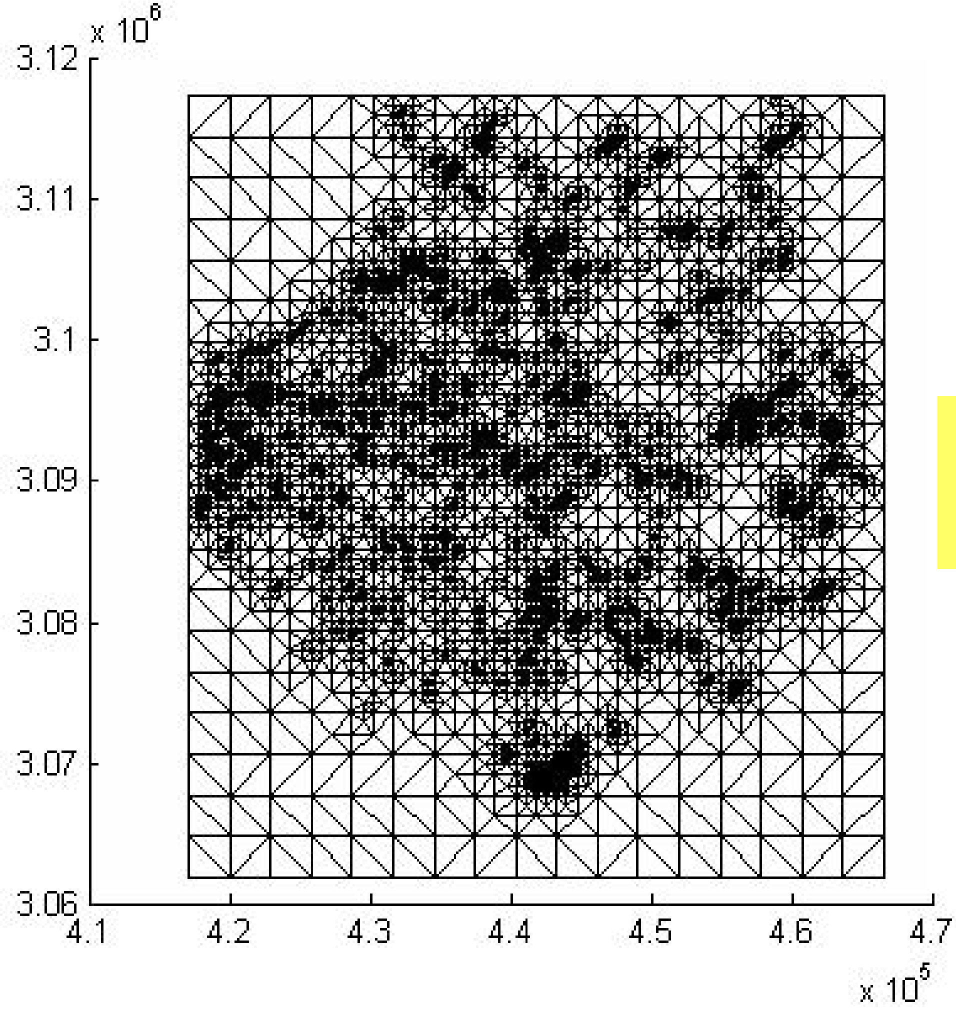
Contour map of Gran Canaria

Numerical experiments



Albedo map of Gran Canaria

Numerical experiments

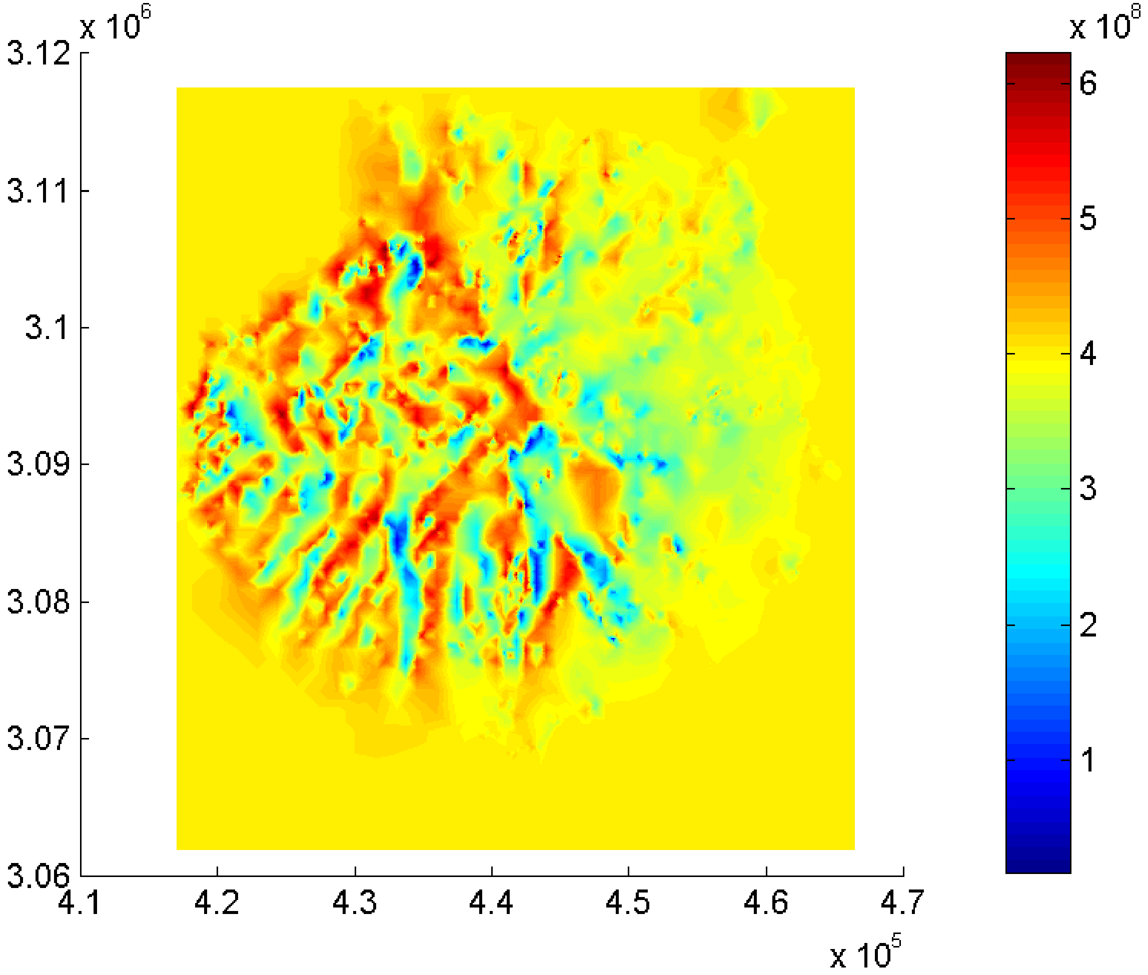


5866 nodes
11683 triangles

Triangular mesh adapted to topography and albedo

Numerical experiments

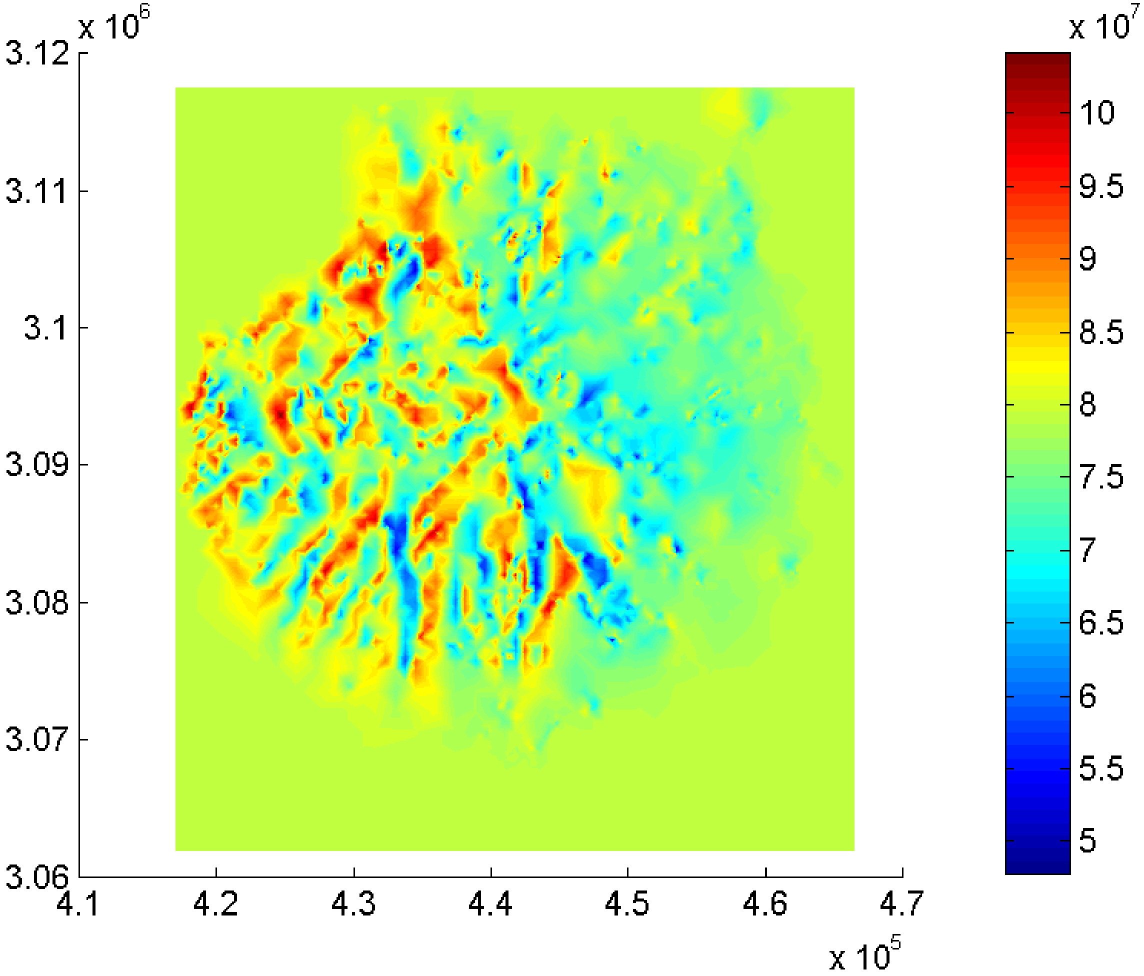
82 – 83% of the mean global irradiation



Beam radiation map (J/m^2)
relative to December 2006

Numerical experiments

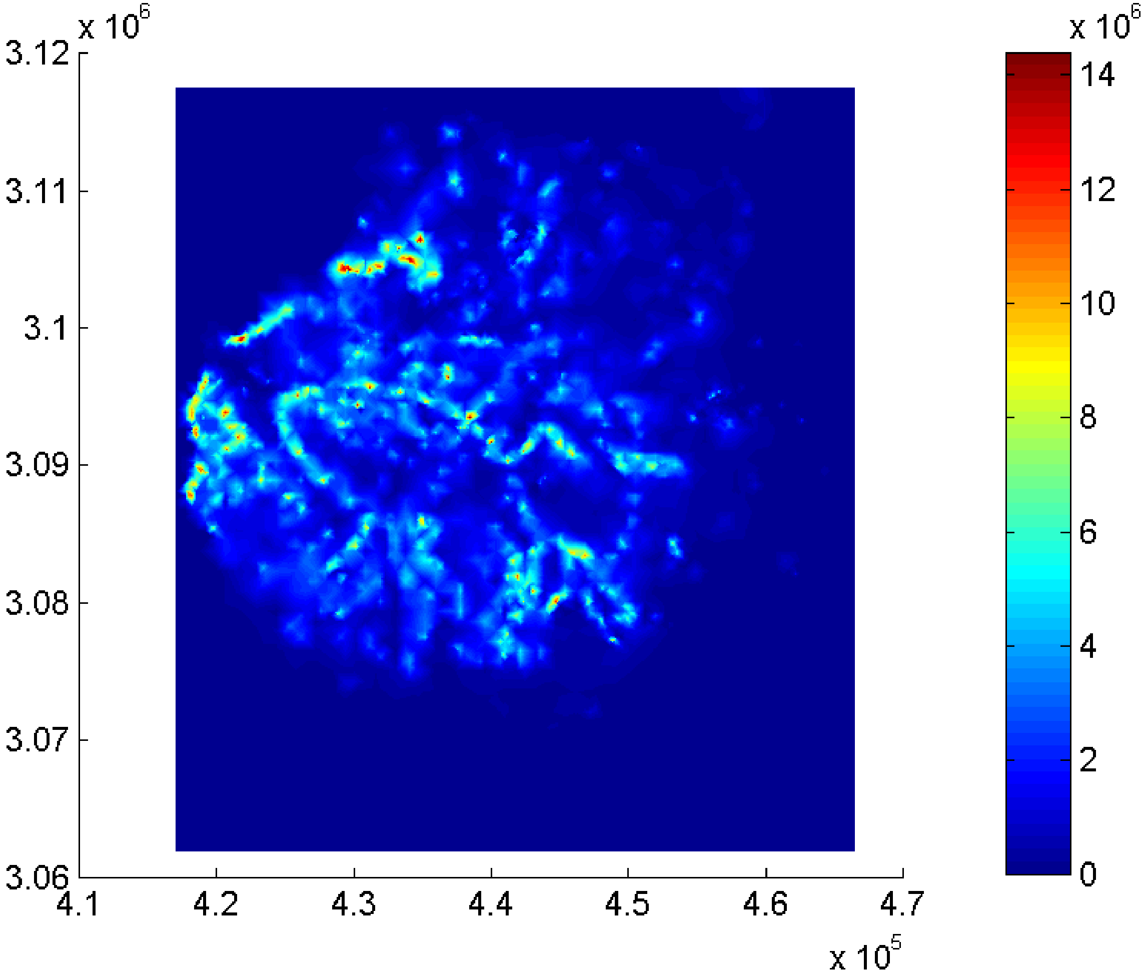
16 – 17% of the mean global irradiation



Diffuse radiation map (J/m^2) relative to December 2006

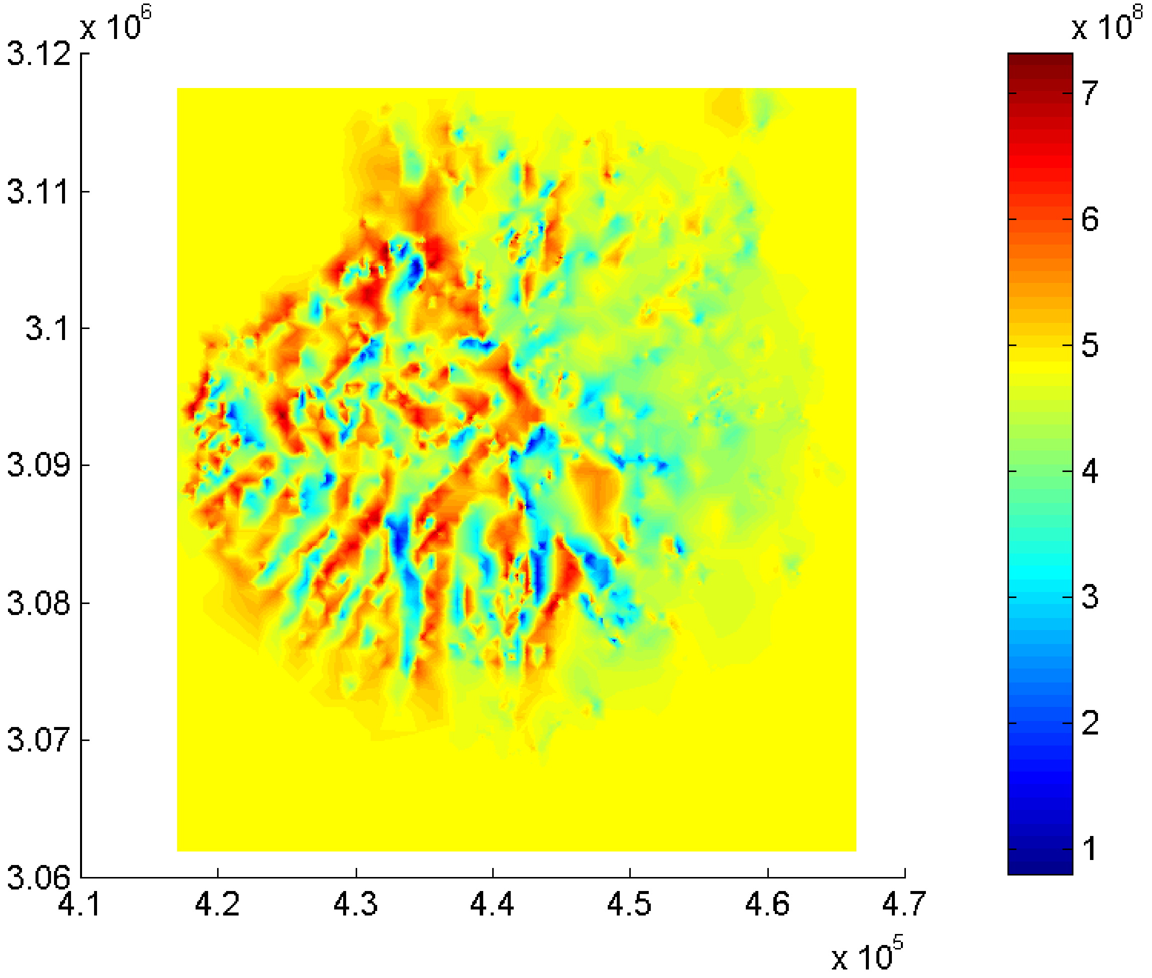
Numerical experiments

0 – 0.4% of the mean global irradiation



Reflected radiation map (J/m^2) relative to December 2006

Numerical experiments

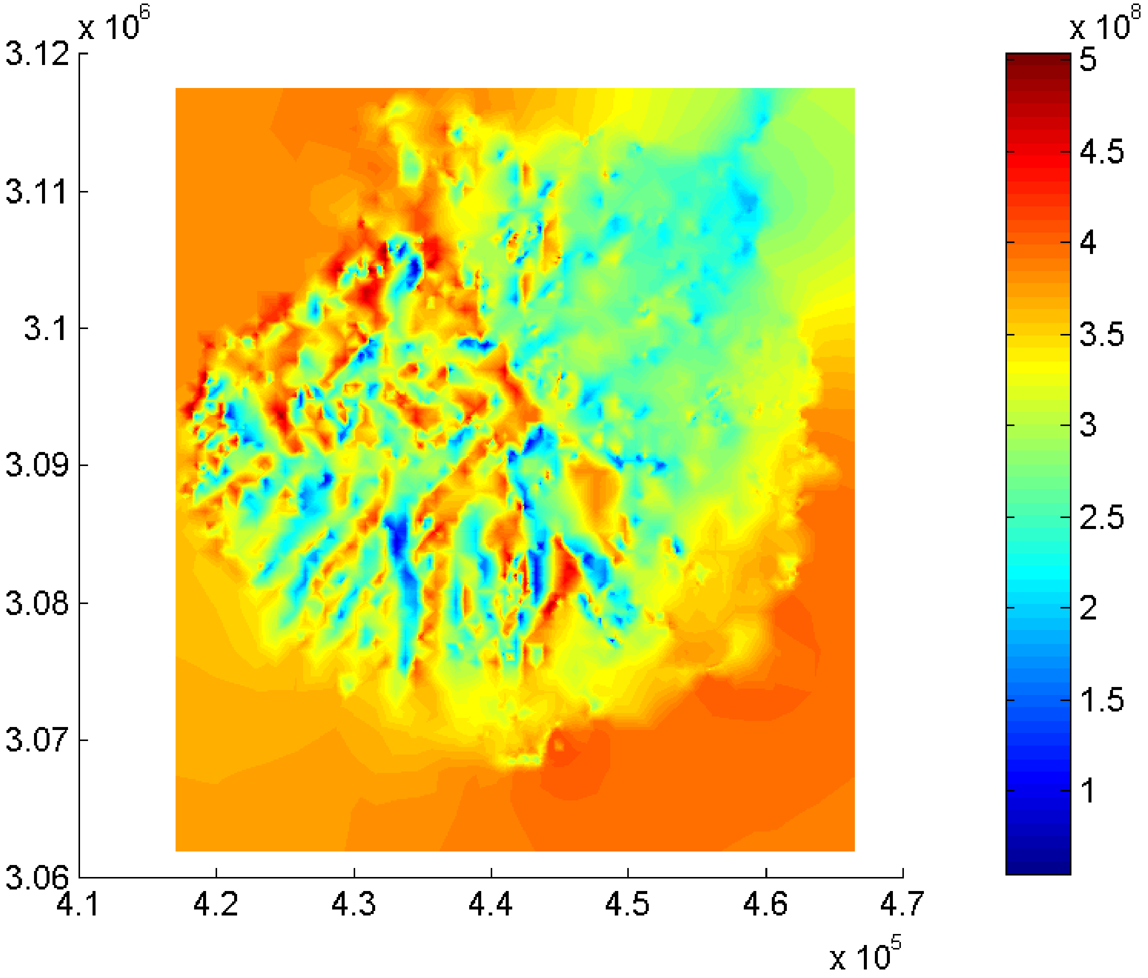


Clear sky global radiation map (J/m^2)
relative to December 2006

Numerical experiments

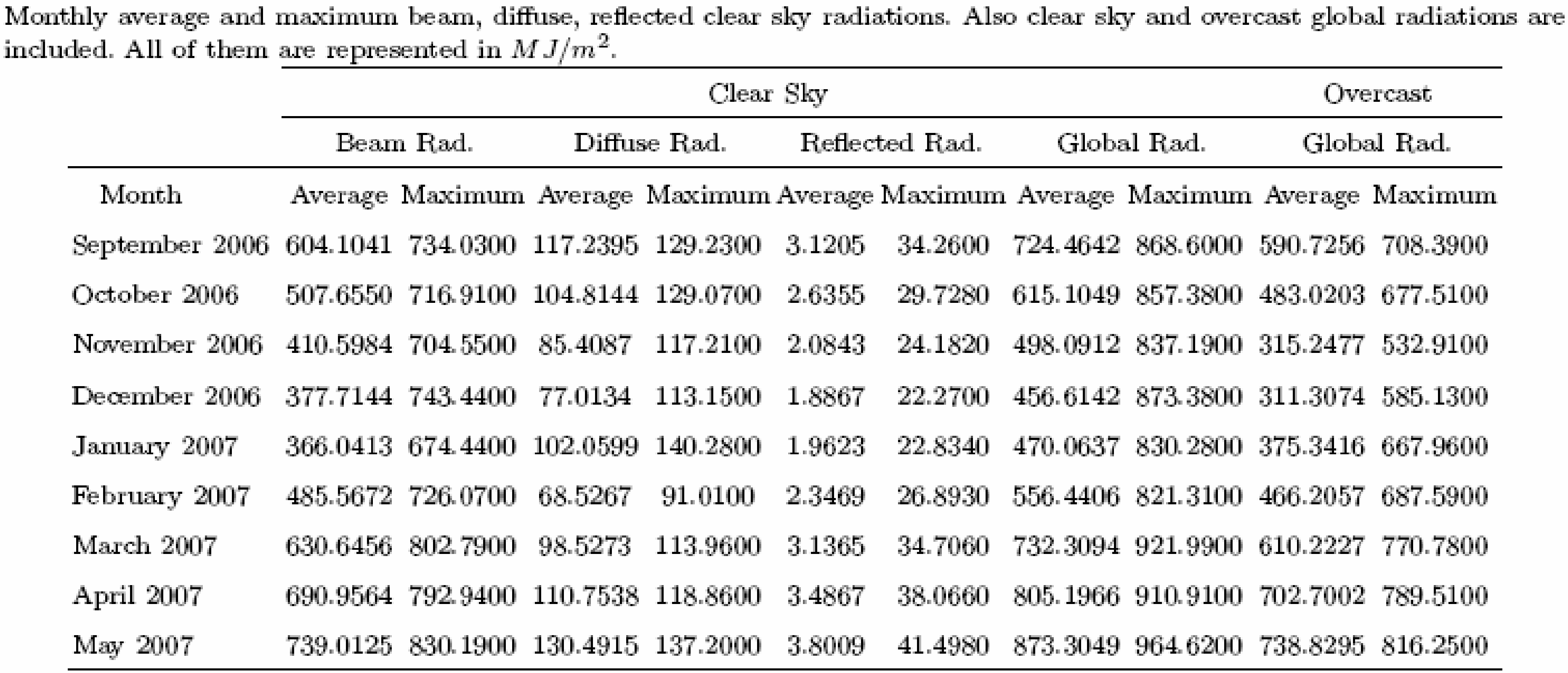
Correction in some overcast days reduced the clear sky results from 20% to the 70% (winter)

April: 1% to 30%



Overcast global radiation map (J/m^2) relative to December 2006

Numerical experiments



Monthly average and maximum beam, diffuse, reflected clear sky radiations. Also clear sky and overcast global radiations are included. All of them are represented in MJ/m^2.

	Clear Sky								Overcast	
	Beam Rad.		Diffuse Rad.		Reflected Rad.		Global Rad.		Global Rad.	
Month	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
September 2006	604.1041	734.0300	117.2395	129.2300	3.1205	34.2600	724.4642	868.6000	590.7256	708.3900
October 2006	507.6550	716.9100	104.8144	129.0700	2.6355	29.7280	615.1049	857.3800	483.0203	677.5100
November 2006	410.5984	704.5500	85.4087	117.2100	2.0843	24.1820	498.0912	837.1900	315.2477	532.9100
December 2006	377.7144	743.4400	77.0134	113.1500	1.8867	22.2700	456.6142	873.3800	311.3074	585.1300
January 2007	366.0413	674.4400	102.0599	140.2800	1.9623	22.8340	470.0637	830.2800	375.3416	667.9600
February 2007	485.5672	726.0700	68.5267	91.0100	2.3469	26.8930	556.4406	821.3100	466.2057	687.5900
March 2007	630.6456	802.7900	98.5273	113.9600	3.1365	34.7060	732.3094	921.9900	610.2227	770.7800
April 2007	690.9564	792.9400	110.7538	118.8600	3.4867	38.0660	805.1966	910.9100	702.7002	789.5100
May 2007	739.0125	830.1900	130.4915	137.2000	3.8009	41.4980	873.3049	964.6200	738.8295	816.2500

Conclusions and future research

- The adaptive triangulation related to the topography and albedo is essential in order to obtain accurate results of shadow distribution and solar radiation.
- Adaptive meshes lead to a minimum computational cost, since the number of used triangles is optimum.
- The accuracy of the model results depends on the number of points where we know realistic data.
- One aspect to be improved is the interpolation procedure used for processing such data.
- Some unknown parameters of the model may be estimated using genetic algorithms for minimizing the error between the measures and the results of the model in the observational points.

- Optimal selection of the warning points for detecting the shadows.
- Accurate determination of the shadow boundary with ref/deref. procedure and mesh adaption by moving nodes to such contour line.
- Define any standard error indicator for each triangle in order to ref/deref. the mesh attending to the daily numerical solution of the overcast global radiation.

- The calculation may be fully parallelised.