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A New Predictive Solar Radiation Numerical Model

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http://www.dca.iusiani.ulpgc.es/proyecto2012-2014/html/

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Contents

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Introduction

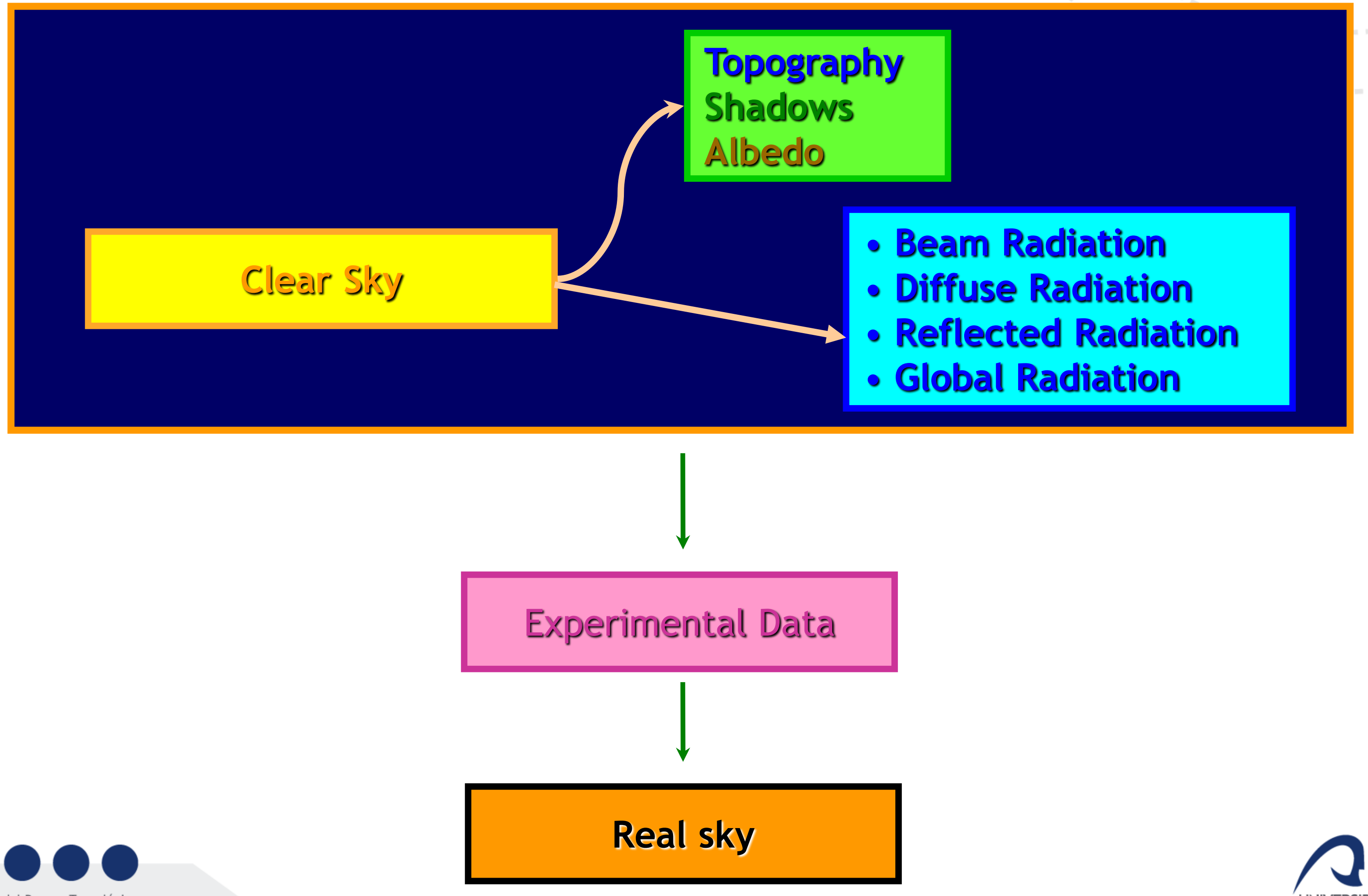
- Solar power is one of the most appreciate renewable energies

- Three groups of factors determine the interaction of solar radiation with the earth's atmosphere and surface
  - a. 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)

- Correct estimation needs an accurate definition of the terrain surface and the produced shadows. Previous works (SE 2009, ECT 2010, JCAM 2012)

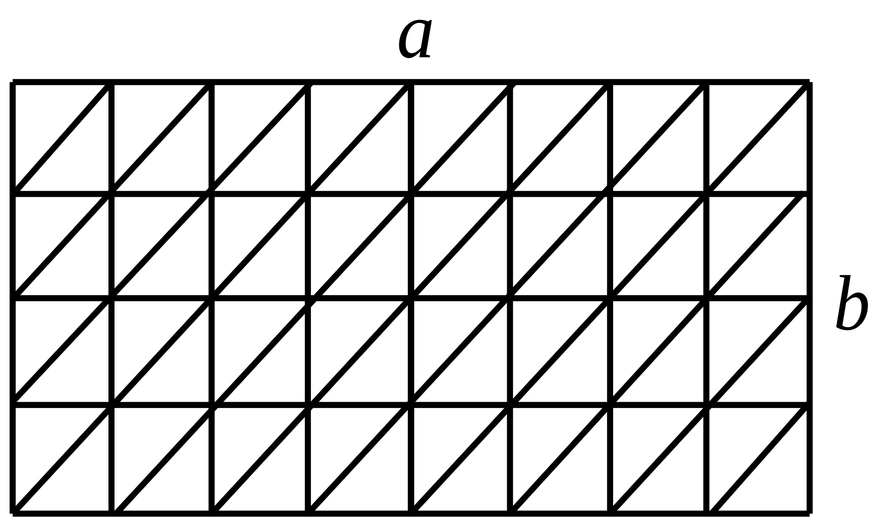
- A typical meteorological year (TMY) for each available measurement station has been developed.

Introduction



Terrain surface mesh and shadows

Build a sequence of nested meshes from a uniform triangulation of a rectangular region, such that the mesh level l is obtained by a global refinement of the previous level $l-1$ with the 4-T Rivara's algorithm



(uniform initial mesh)

Terrain surface mesh and shadows

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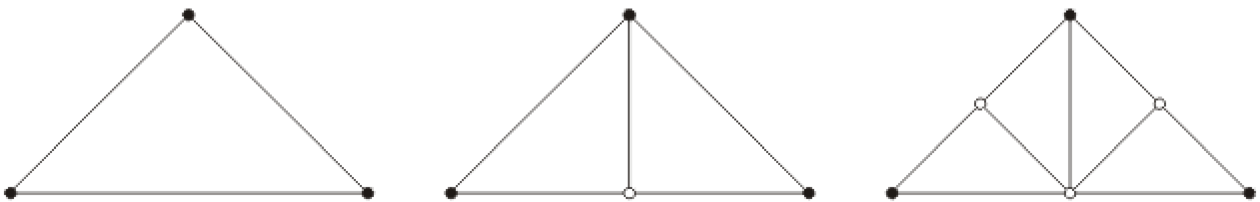
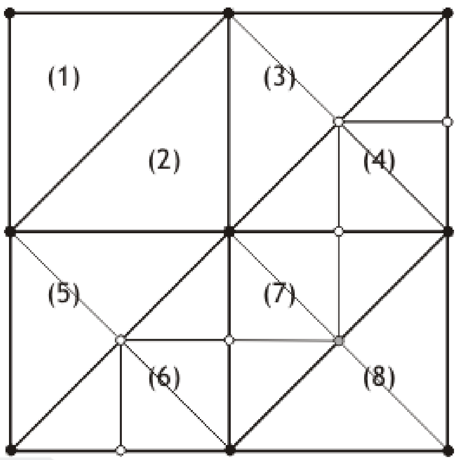
Build a sequence of nested meshes from a uniform triangulation of a rectangular region, such that the mesh level *l* is obtained by a global refinement of the previous level *l*−1 with the 4-T Rivara's algorithm



(a) (b) (c)



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Terrain surface mesh and shadows

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Build a sequence of nested meshes from a uniform triangulation of a rectangular region, such that the mesh level l is obtained by a global refinement of the previous level $l-1$ with the 4-T Rivara's algorithm

The number of levels m of the sequence is determined by the resolution of the terrain elevation map

Define a new sequence applying a derefinement algorithm. The number of levels of the derefined sequence is $m' \leq m$

Two derefinement parameters, ε_h and ε_a , are introduced and they determine the accuracy of the approximation to terrain surface and albedo, respectively.

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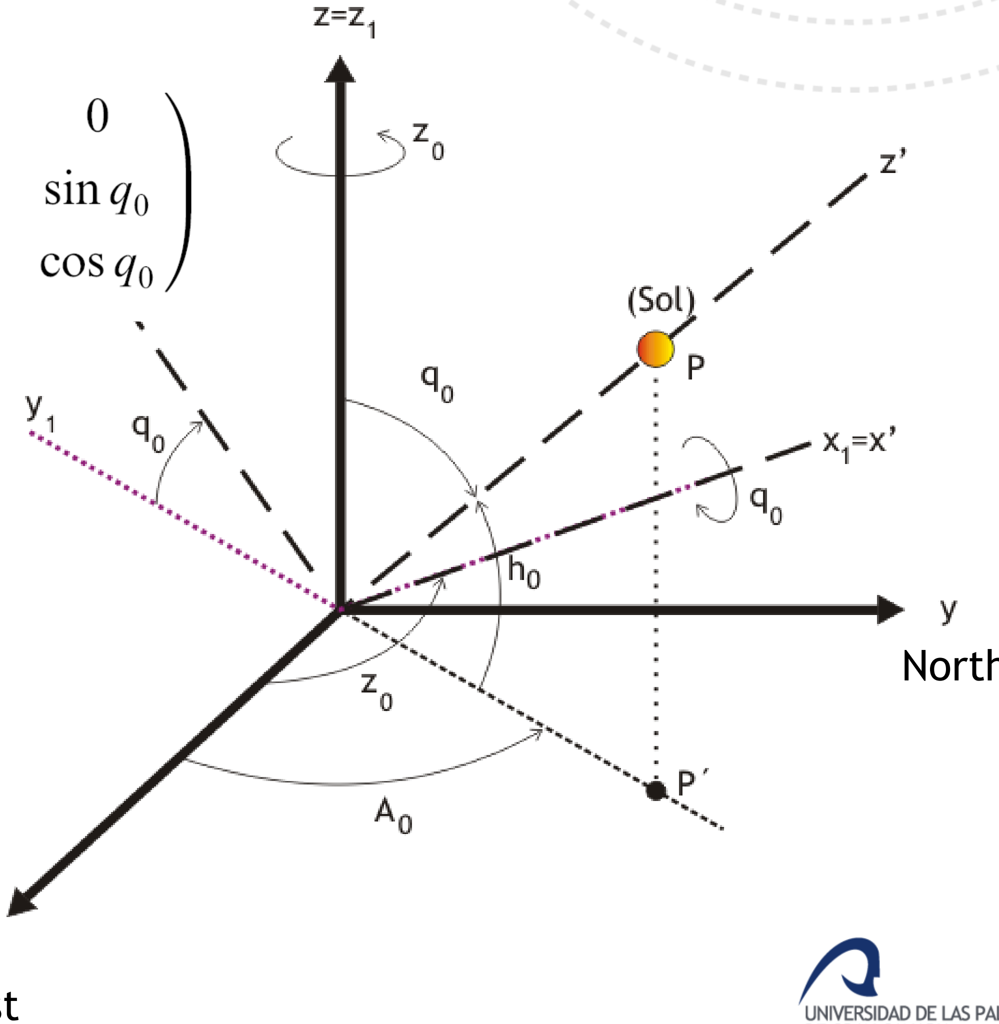
Terrain surface mesh and shadows

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'*

$$K = \begin{pmatrix} \cos z_0 & \sin z_0 & 0 \\ -\cos q_0 \ \sin z_0 & \cos q_0 \ \cos z_0 & \sin q_0 \\ \sin q_0 \ \sin z_0 & -\cos z_0 \ \sin q_0 & \cos q_0 \end{pmatrix}$$

$$v_{sun} = \begin{pmatrix} \cos h_0 \cos A_0 \\ \cos h_0 \sin A_0 \\ \sin h_0 \end{pmatrix}$$



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Terrain surface mesh and shadows

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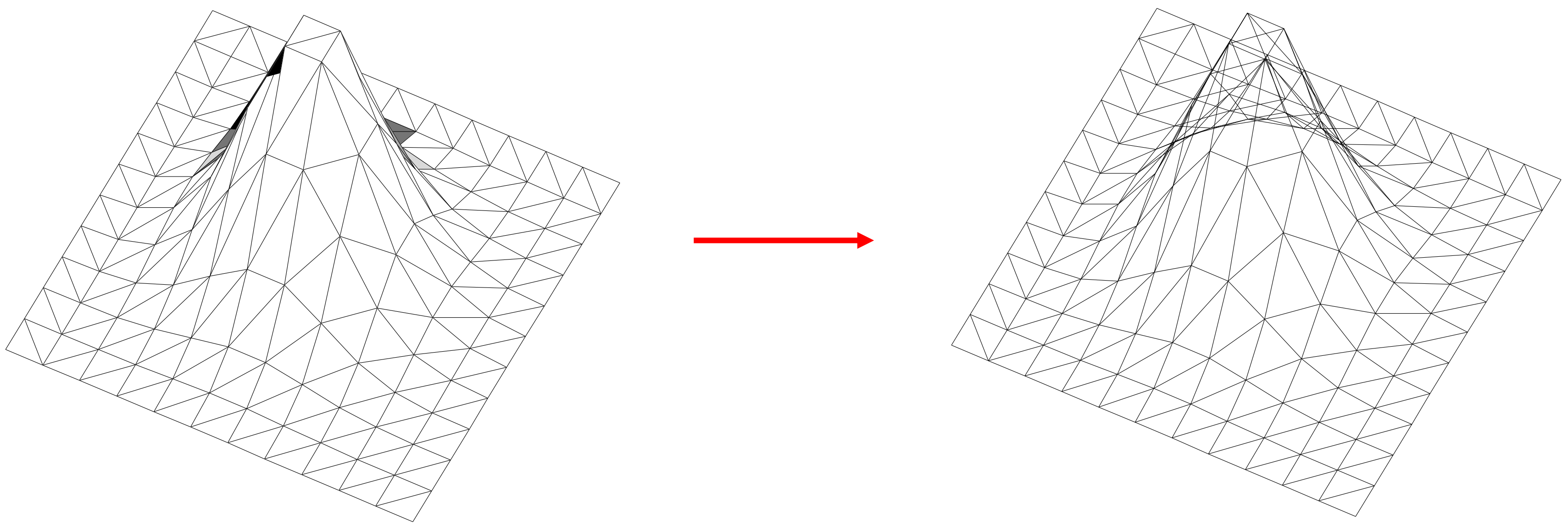
Check for each triangle Δ of the mesh, if there exists another Δ' that intersects Δ and is in front of it, i.e., the z' coordinates of the intersection points of Δ' are greater than those of Δ



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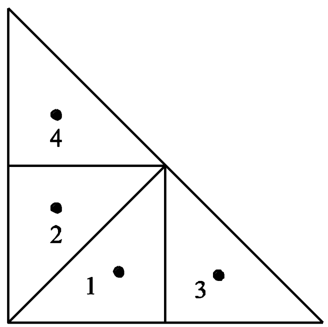
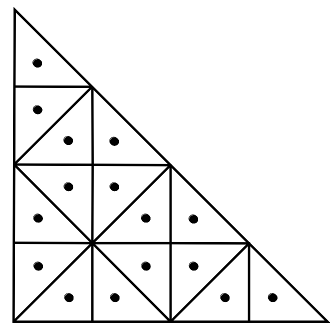
Terrain surface mesh and shadows

The analysis of the intersection between triangles involves a high cost

Therefore, we have considered 4 or 16 warning points (n_{wp})





A light factor, L_f is defined

$$L_{fcs} = \frac{n_{wp} - i}{n_{wp}}$$

$$i = 0, 1, \ldots, n_{wp}$$

$$L_f = L_{fcs} \cdot L_{fss}$$

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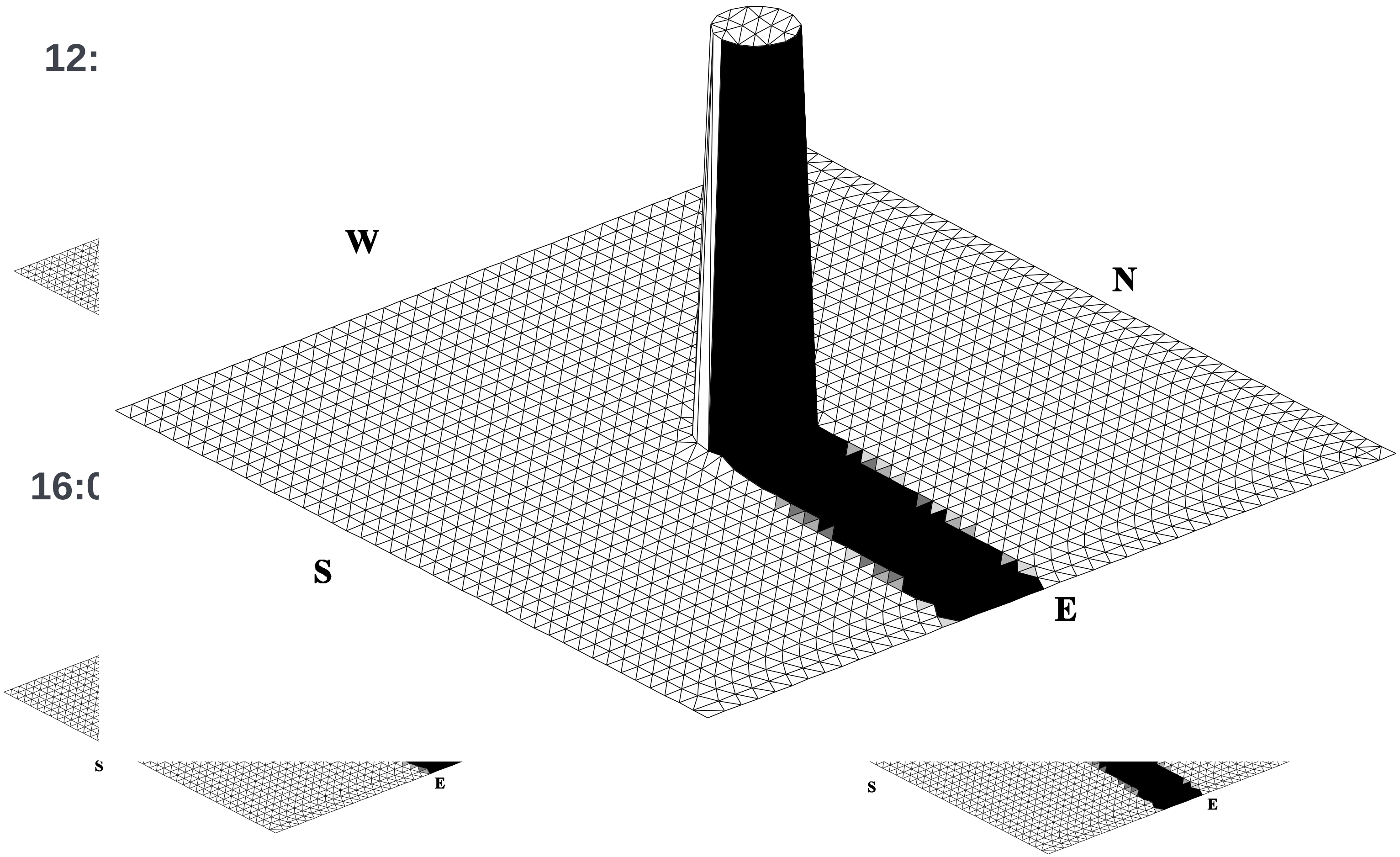
Terrain surface mesh and shadows



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Solar radiation modelling

General aspects:

We have introduced the use of adaptive meshes for surface discretization and a new method for detecting the shadows over each triangle of the surface.

Calculations flow:

1. We first calculate the solar radiation under the assumption of clear sky for all the triangles of the mesh.

2. Typical Meteorological Year (TMY) is evaluated for all the involved measurement stations.

3. Solar radiation values are corrected for a real sky by using the TMY from the available data of the measurement stations in each time step along an episode.

Steps 1 and 3 are repeated for each time step and finally, the total solar radiation is obtained integrating all the instantaneous values in each triangle.

Solar radiation equations for clear sky

Beam radiation

Extraterrestrial irradiance G_0 normal to the solar beam

$$G_0 = I_0 \epsilon$$

Solar constant: I_0

Correction factor: ϵ

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

Beam irradiance normal to the solar beam

$$G_{b0c} = G_0 \, exp\{-0{,}8662 T_{LK} m \delta_R(m)\}$$

T_{LK}: Linke atmospheric turbidity factor

m: Relative optical air mass

Beam irradiance on a horizontal surface

$$G_{bc}(0) = G_{b0c} \, L_f \, K_\delta = G_{b0c} \, L_f \, \mathrm{sen}(h_0)$$

h_0: the solar altitude angle

L_f: the light factor

Beam irradiance on an inclined surface

$$G_{bc}(\beta) = G_{b0c} \, L_f \, K_\delta = G_{b0c} L_f \cos(\delta_{exp})$$

δ_{exp}: the incidence solar angle

Solar radiation modelling

Solar radiation equations for clear sky

Diffuse radiation

Diffuse radiation on horizontal surfaces

$$G_{dc_e}(0) = G_0\, T_n(T_{LK})\, F_d(h_0)$$

Diffuse transmission (T_n)

Function depending on the solar altitude (F_d)

Diffuse radiation on inclined surfaces

Sunlit surfaces

$h_o \geq 0.1$

$$G_{dc}(\beta) = G_{dc_e}(0)\left[F(\beta)(1-K_b) + K_b\frac{K_\delta}{\text{sen}\, h_0}\right]$$

$$G_{dc}(0) = G_{dc_e}(0)$$

$$K_b = G_{bc}(0)/G_0(0)$$

$$G_0(0) = G_0 \sin h_0$$

$h_o < 0.1$

$$G_{dc}(\beta) = G_{dc_e}(0)\left[F(\beta)(1-K_b) + K_b\frac{\text{sen}\beta\ \cos A_{LN}}{0,1-0,008\, h_0}\right]$$

$$G_{dc}(0) = G_{dc_e}(0)\ (1-K_b)$$

Shadowed surfaces

$$G_{dc}(\beta) = G_{dc_e}(0)\ F(\beta)$$

$$G_{dc}(0) = G_{dc_e}(0)$$

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Solar radiation equations for clear sky

Reflected radiation

$$G_r(\beta) = \rho_g G_c(0) r_g(\beta)$$

Mean ground albedo

$$r_g(\beta) = \frac{1-\cos\beta}{2}$$

$$G_c(0) = G_{bc}(0) + G_{dc}(0)$$

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Solar radiation modelling

Solar radiation under real-sky

Values of global radiation on a horizontal surface for real sky conditions *G(0)* are calculated as a correction of those of clear sky $G_c(0)$ with the clear sky index k_c

$$G(0) = G_c(0) k_c$$

If some measures of global radiation $G_s(0)$ are available at different measurement stations, s , the value of the clear sky index at those points may be computed as

$$k_{cs} = G_s(0)/G_c(0)$$

Then k_c may be interpolated in the whole studied domain, for example:

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

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Solar radiation modelling

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Typical Meteorological Year (TMY)

To obtain accurate real sky values of global irradiation, the evaluation of a TMY is used to avoid results based on a particular year weather conditions

For each station, we compute the daily typical meteorological year of irradiation values using weight means to smooth the irregular data.

For example, we can use the following statistic metrics:

Means

$$\hat{m}_d = \frac{1}{A}\sum_{a=1}^{A} M_{21} Z_{ad} \qquad d = 1, 2, \ldots, 365$$

Medians

$$M'_d = median(Z_{ad}) \qquad a = 1, \ldots, A \qquad d = 1, 2, \ldots, 365$$

$$M_d = M_{21} M'_d \qquad d = 1, 2, \ldots, 365$$

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Solar Model Summary

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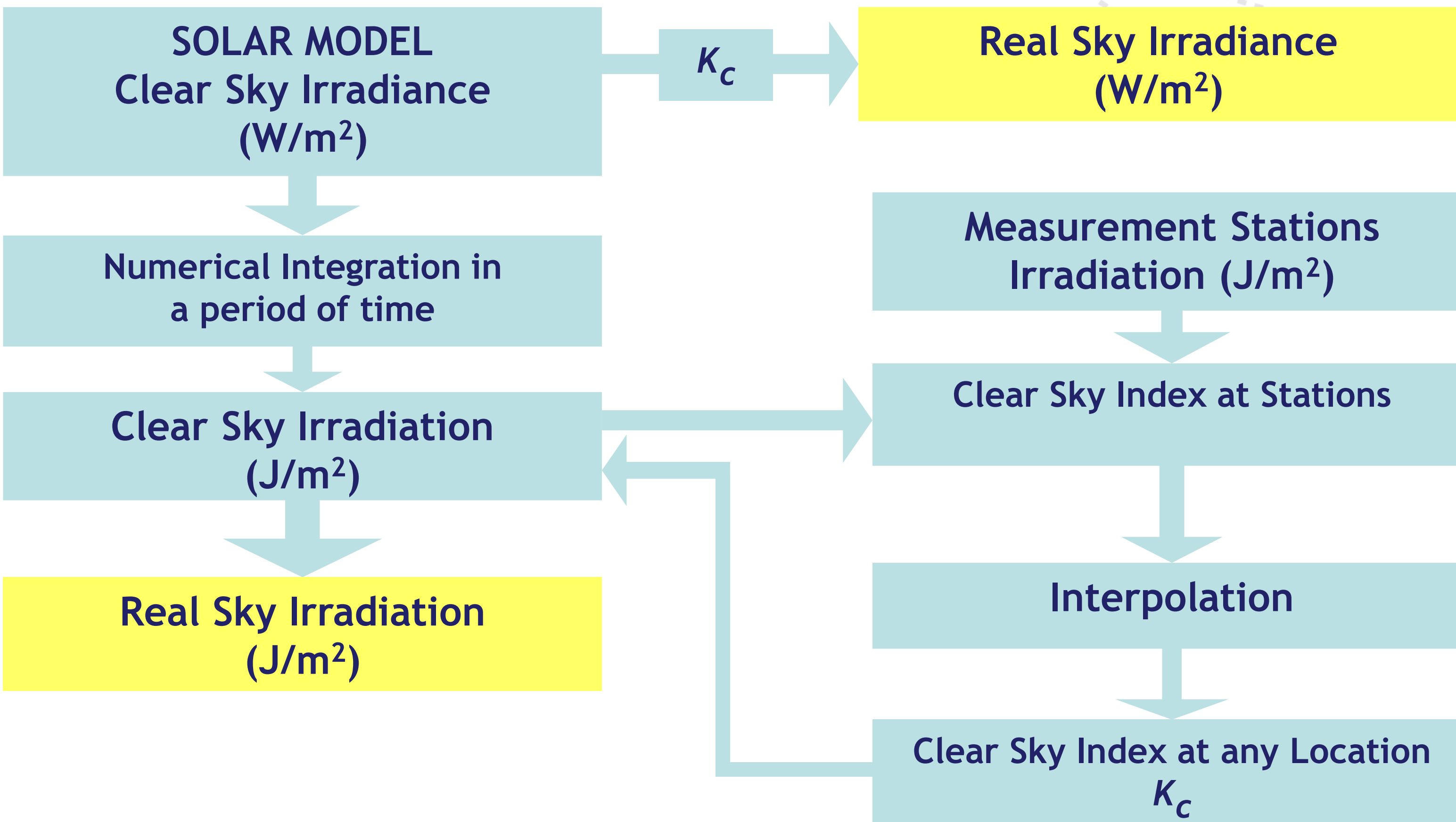

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Predictive Model

Solar generation problem: Randomness of primary energy

Predictive Model

Real sky radiation values will be computed starting from clear sky ones, replacing the stations measurements values by those obtained through the forecasting weather model.

We get one k_{ci} for every time step and each triangle

$$k_{c_i} = \frac{G(0)}{G_{c_{ss}}(0)}$$

$G(0)$ → MM5

$G_{c_{ss}}(0)$ → Solar Model

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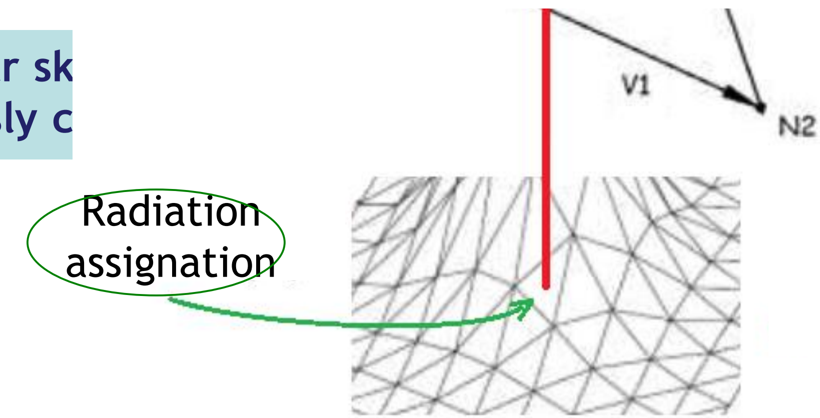
Predictive Model

How to obtain k_{ci}?

1. Trian ... odes
   are t
   radia
2. The ... triangle
   is as
3. The clear sk ... step, using the
   previously c

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} + K_1 \cdot \begin{bmatrix} V_{1_x} \\ V_{1_y} \\ V_{1_z} \end{bmatrix} + K_2 \cdot \begin{bmatrix} V_{2_x} \\ V_{2_y} \\ V_{2_z} \end{bmatrix}$$



Predictive Model

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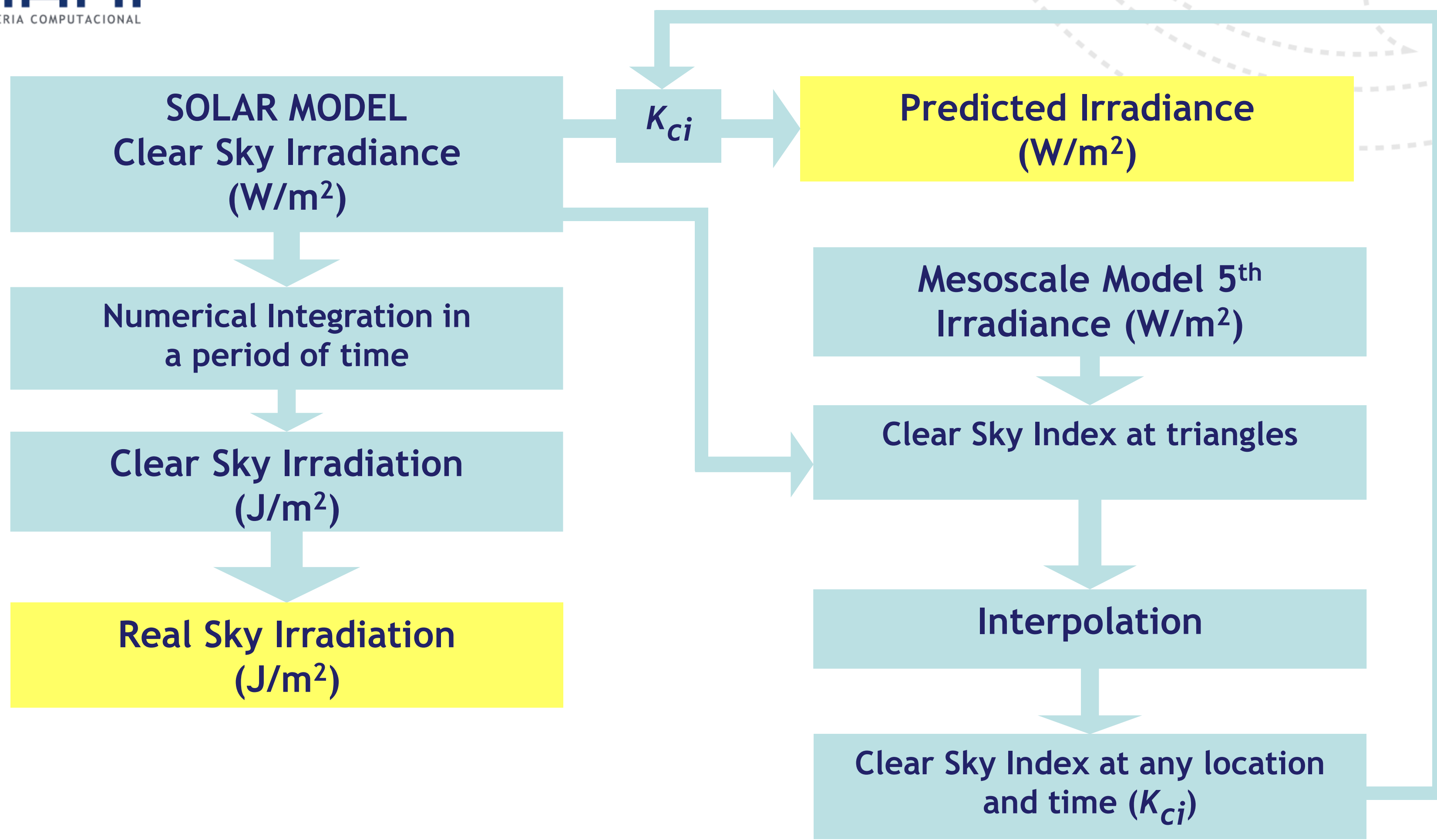
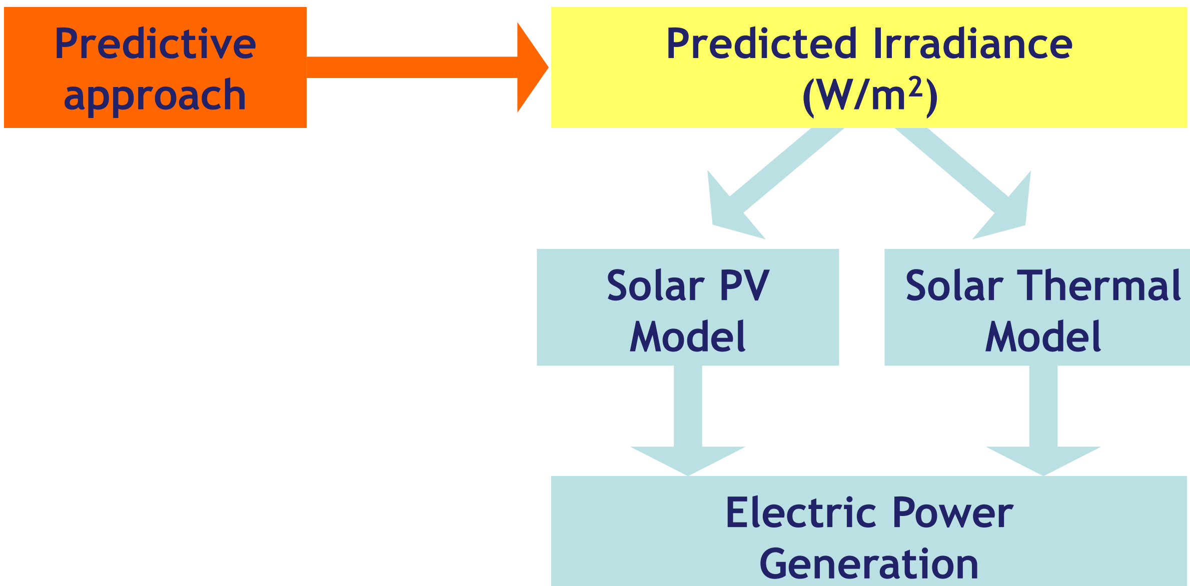


Predictive Model

Solar Power Generation and Electrical Network Management:
Photovoltaic and Solar Thermal



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The studied case corresponds to Gran Canaria, one of the Canary Islands in the Atlantic Ocean at 28.06 latitude and −15.25 longitude.

TMY (199 … d were
obtained …

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Gran Canaria Island

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Results

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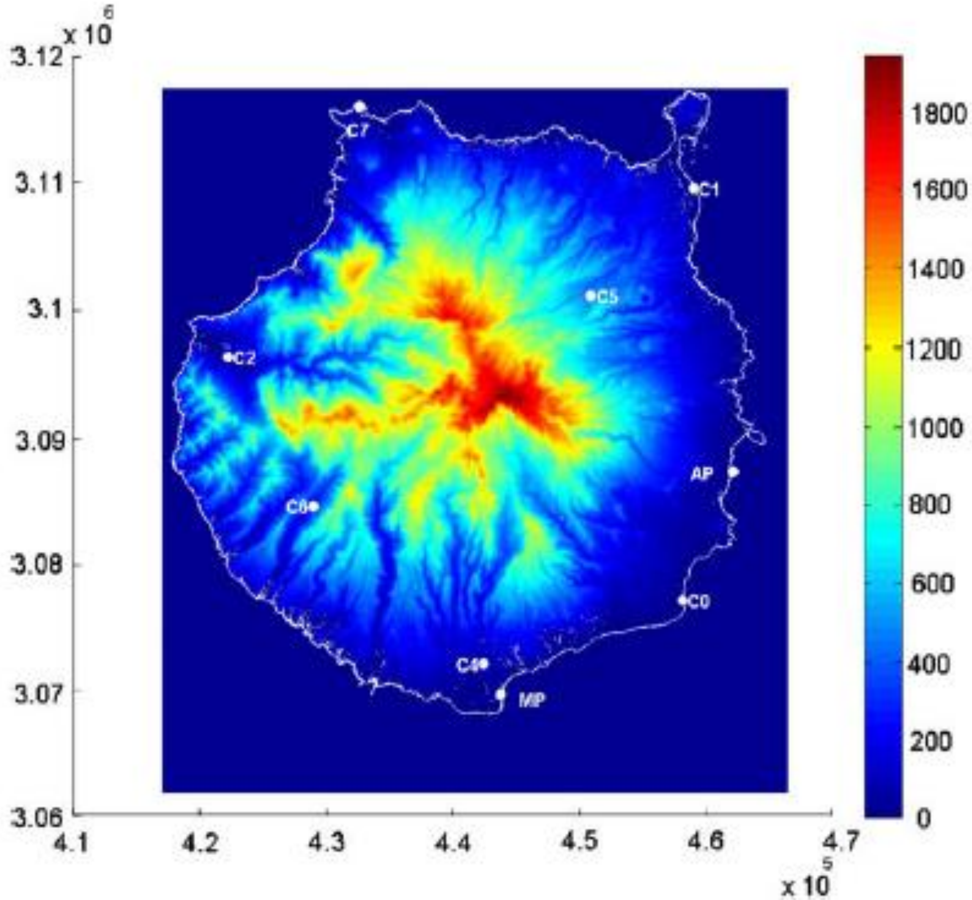
Geolocation of different stations on Gran Canaria Island

Island	label	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



Elevation map of Gran Canaria

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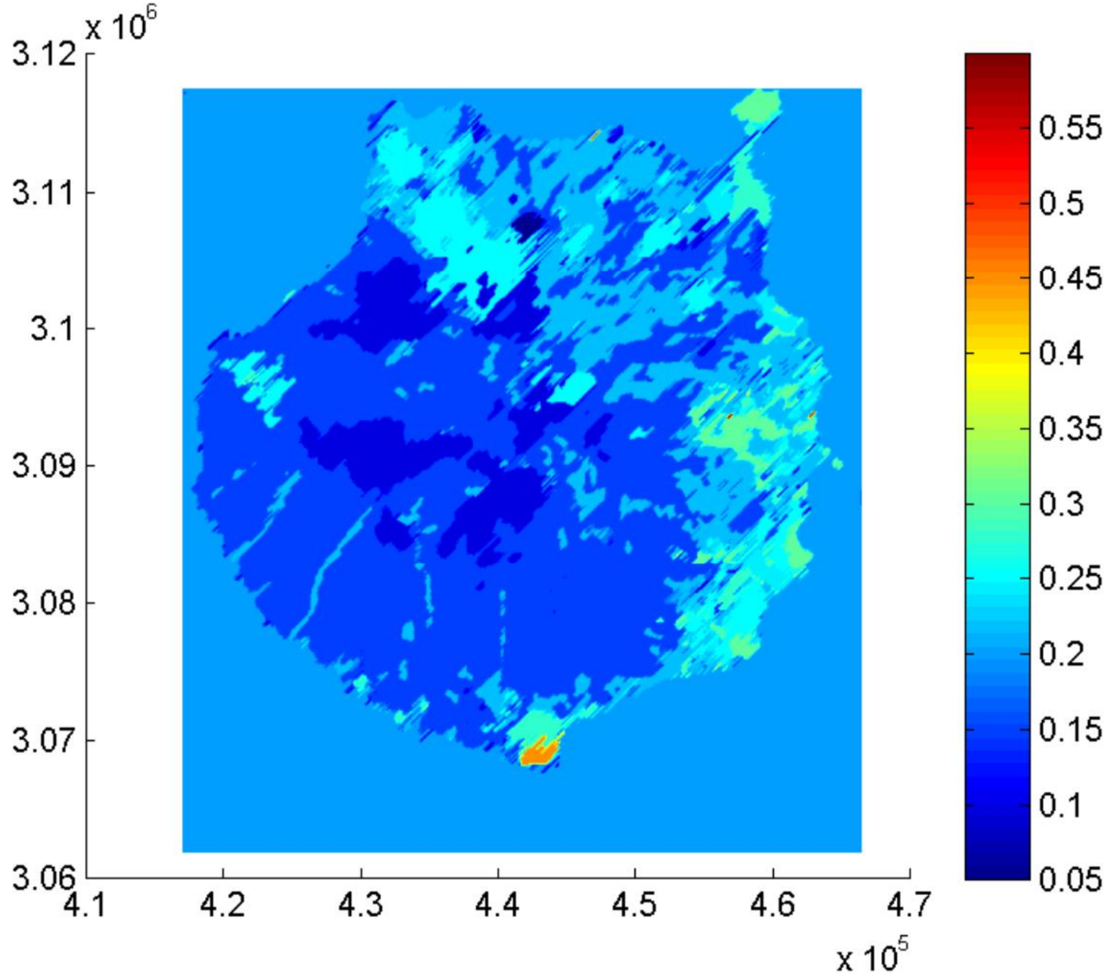
Results

Macaronesic laurisilva

0.05

Salt mine

0.6



Albedo map of Gran Canaria

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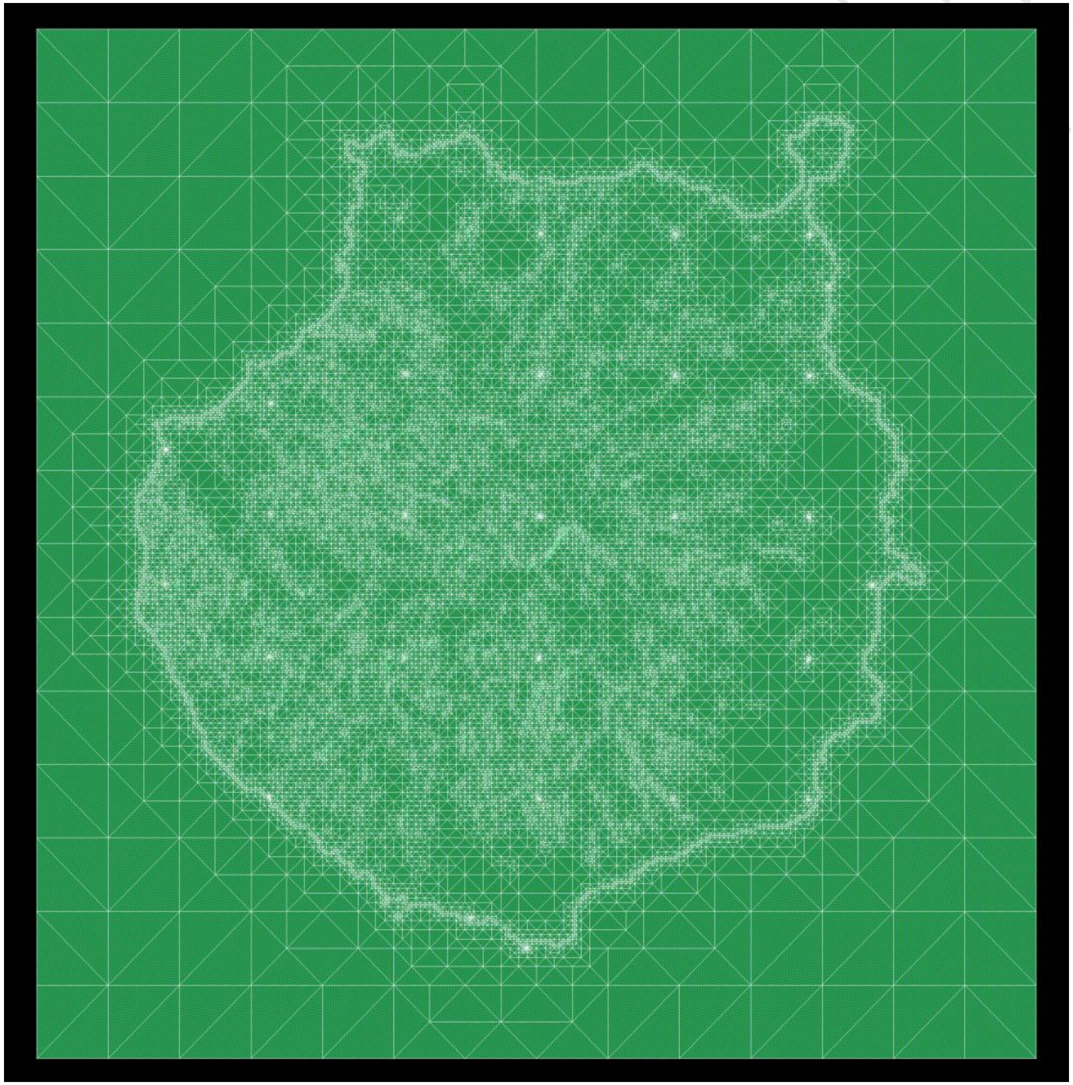
Gran Canaria 2-D Discretization



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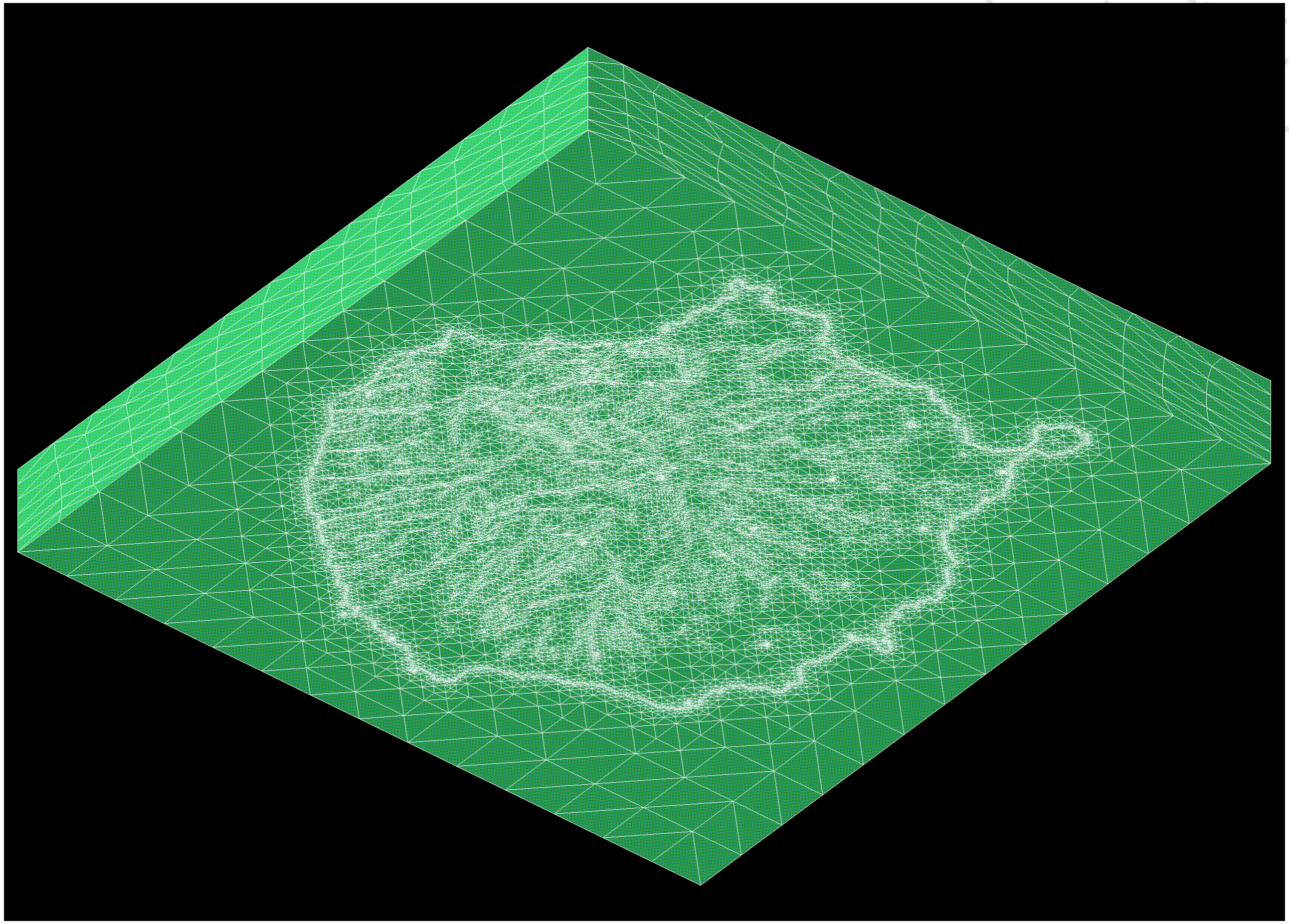
Gran Canaria 3-D Discretization



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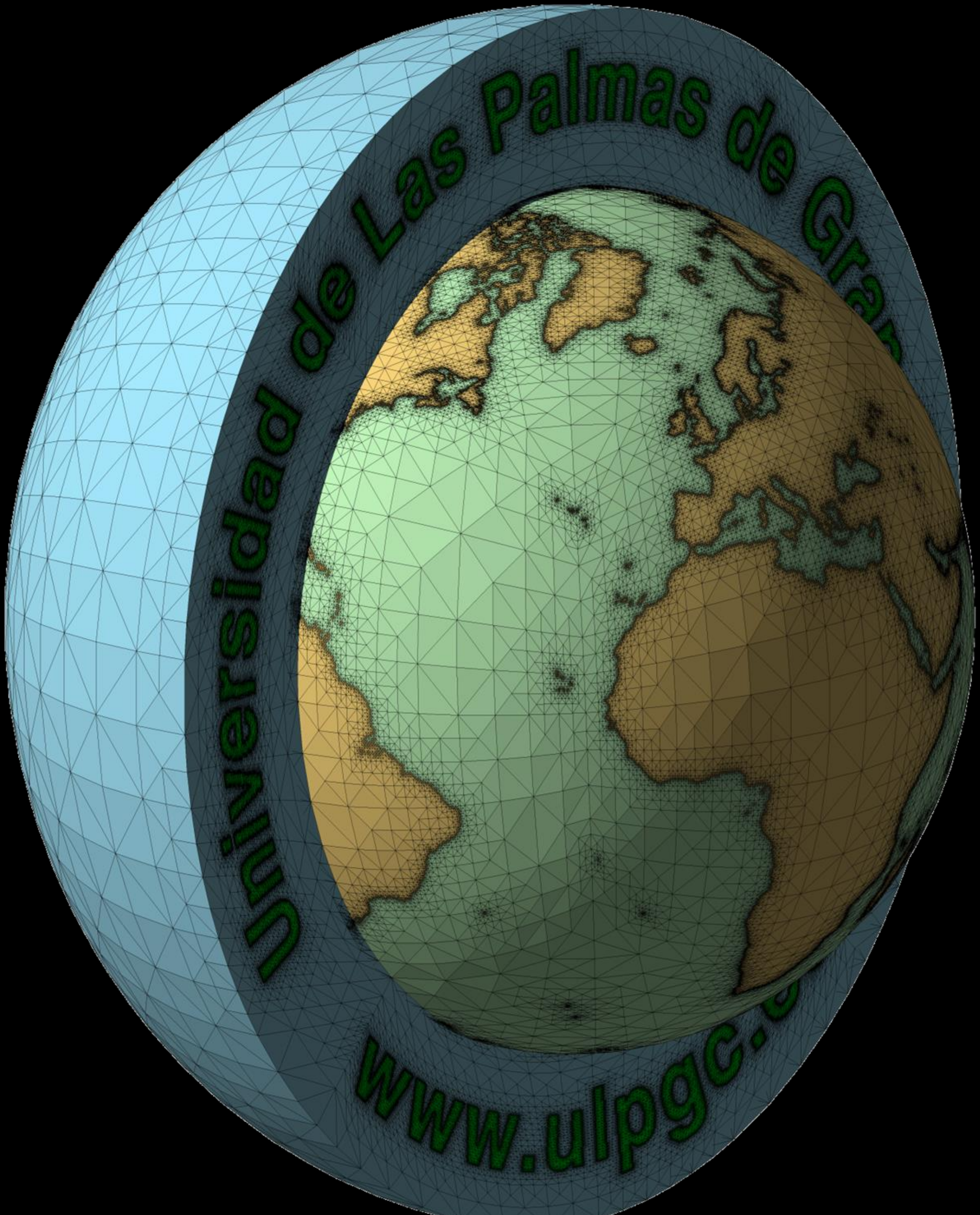
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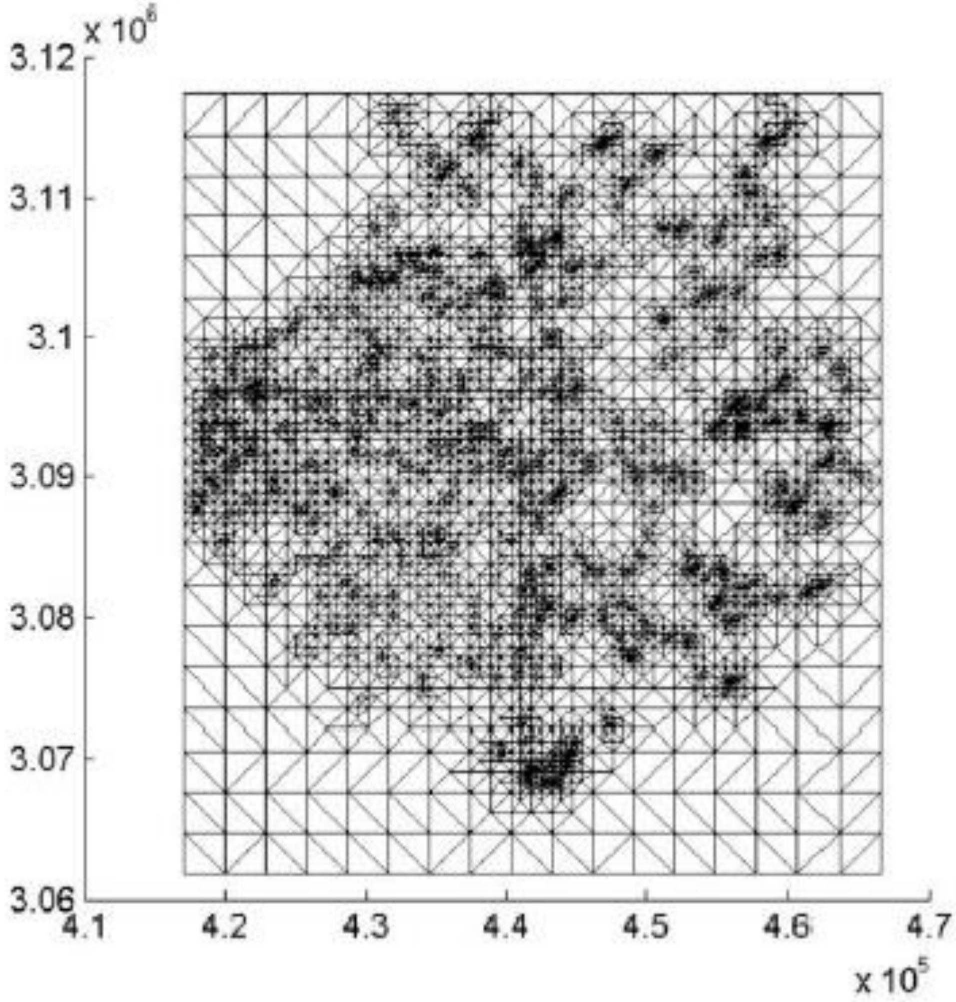

5866 nodes
11683 triangles

Triangular mesh adapted to topography and albedo

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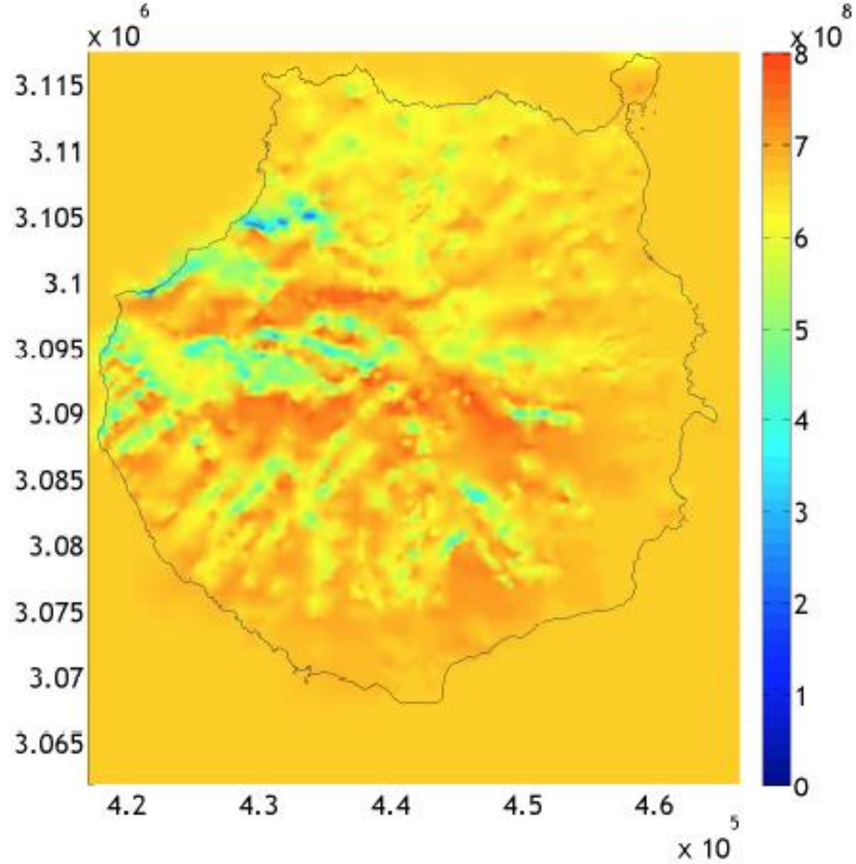
EXAMPLE



Clear sky beam radiation map (J/m^2)
March TMY

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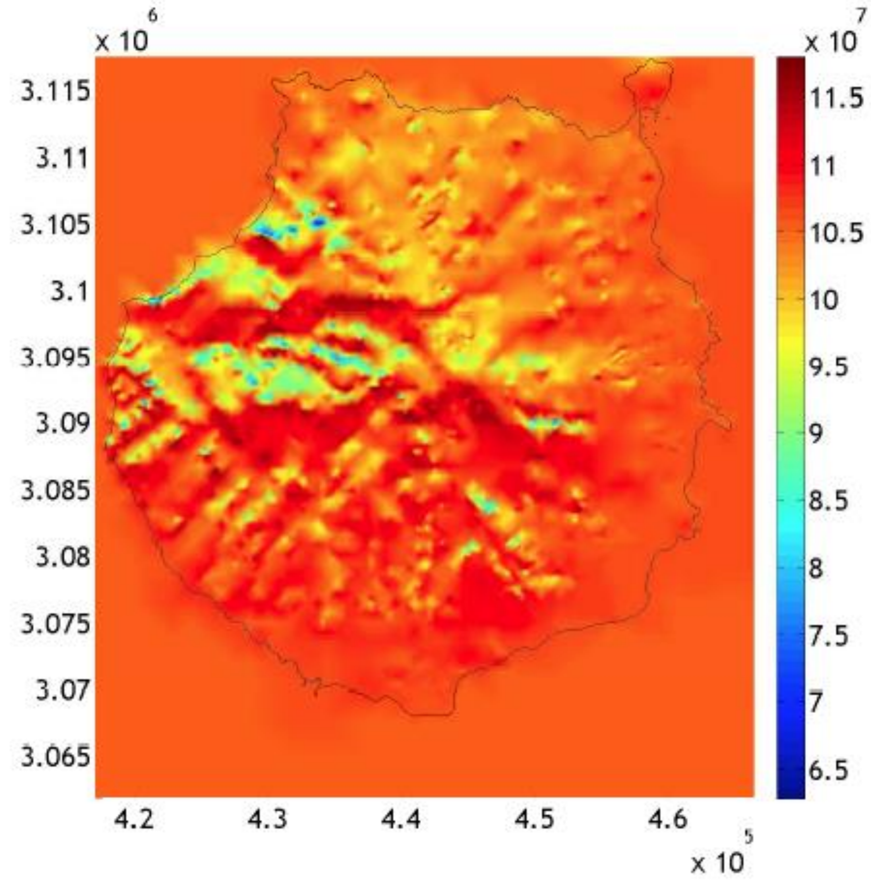

Clear sky diffuse radiation map (J/m^2)
March TMY

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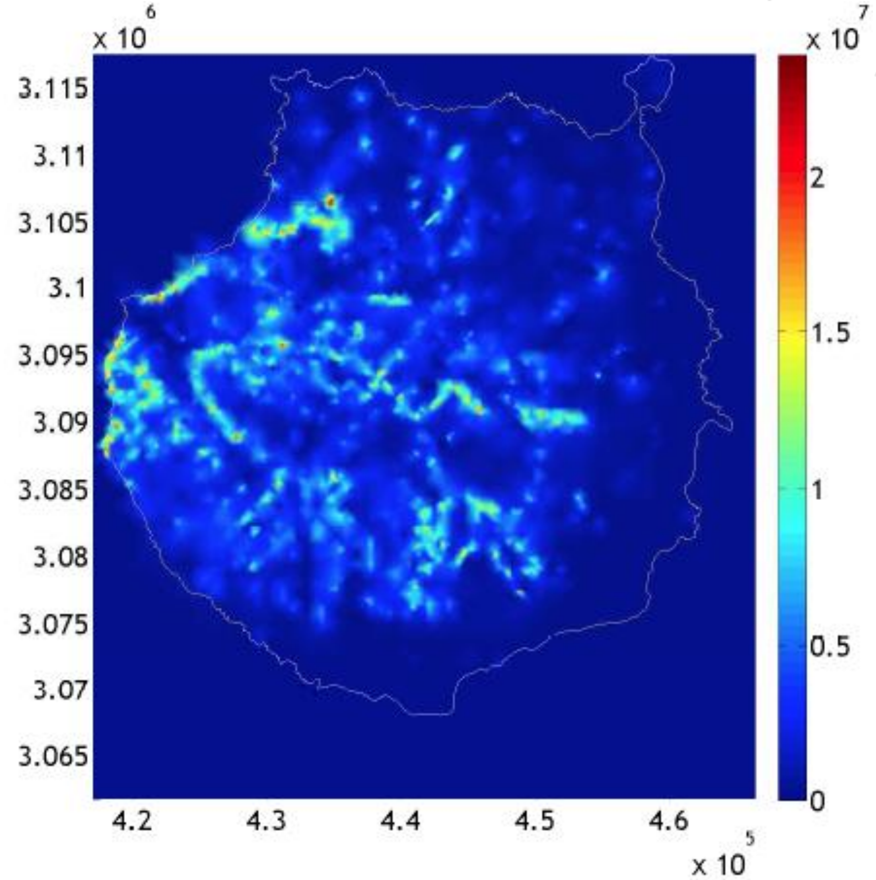

Clear sky reflected radiation map (J/m^2)
March TMY

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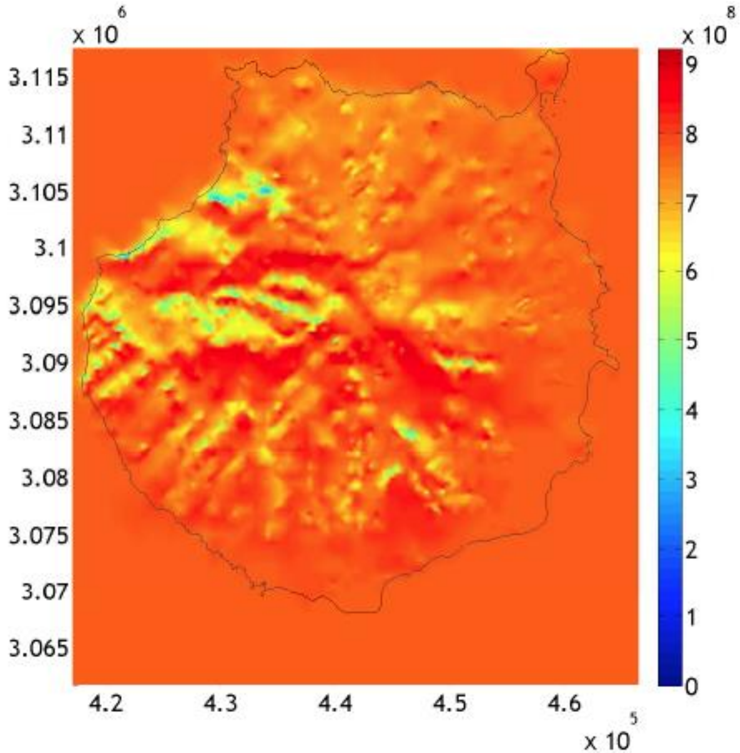
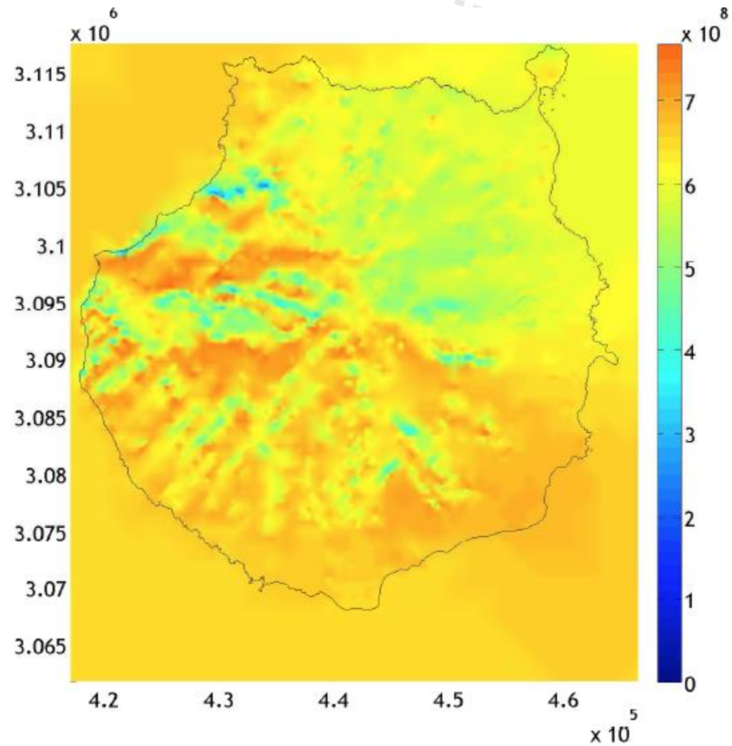


Clear sky global radiation map (J/m²)
March TMY



Real sky global radiation map (J/m²)
March TMY

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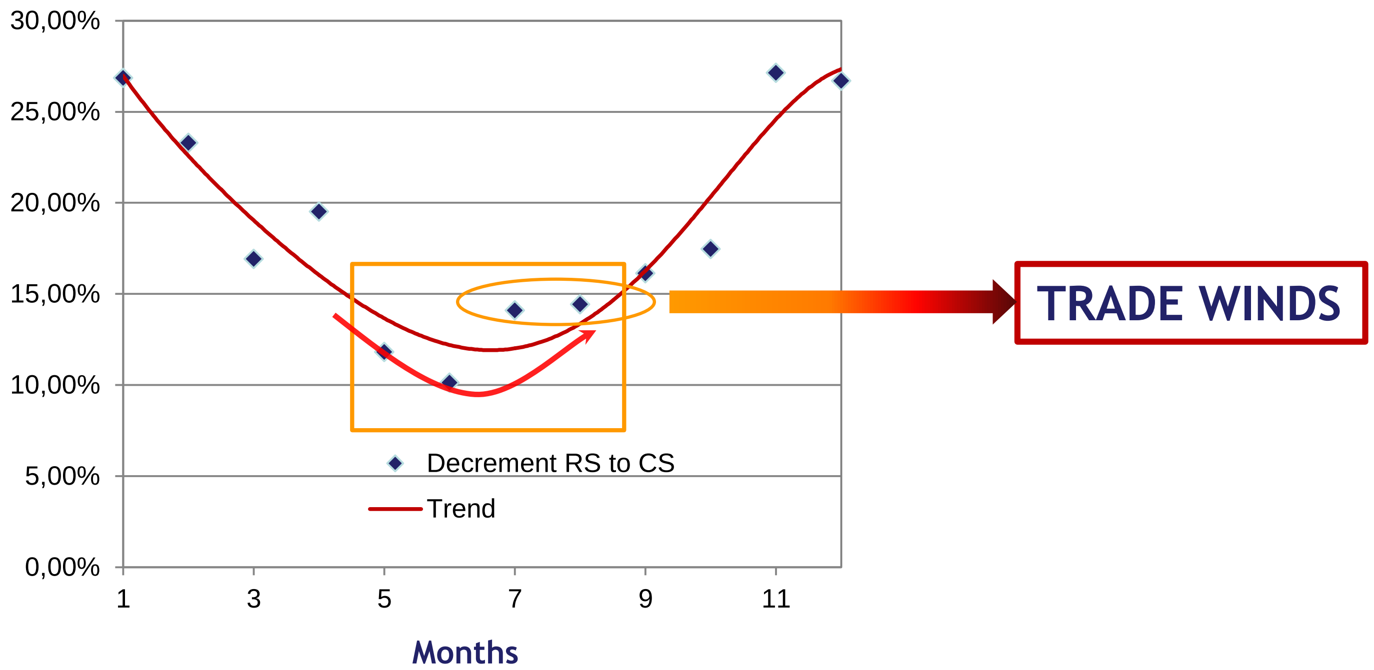
Percentage decrement: Real sky to clear sky



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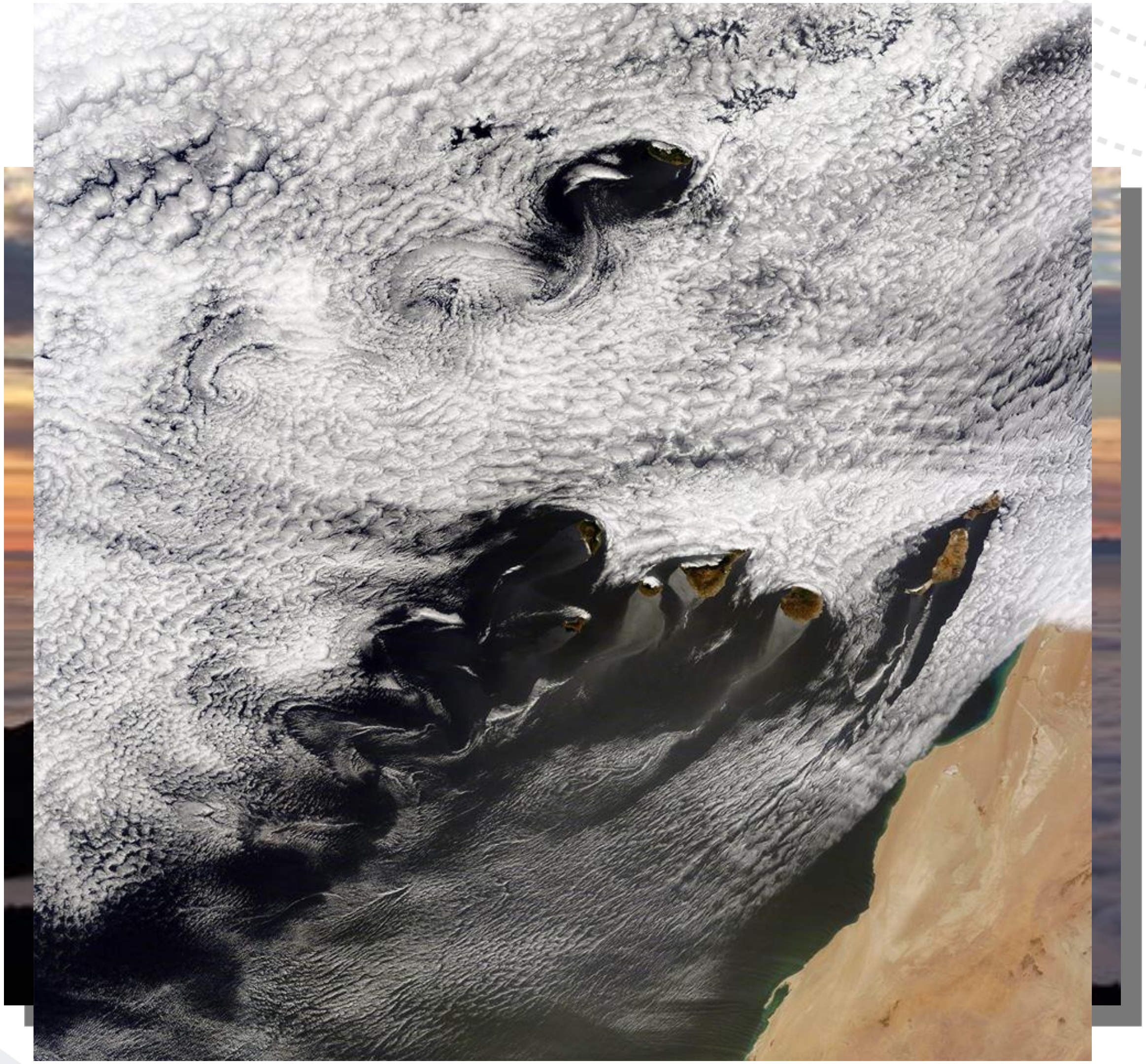
Influence of the trade winds:



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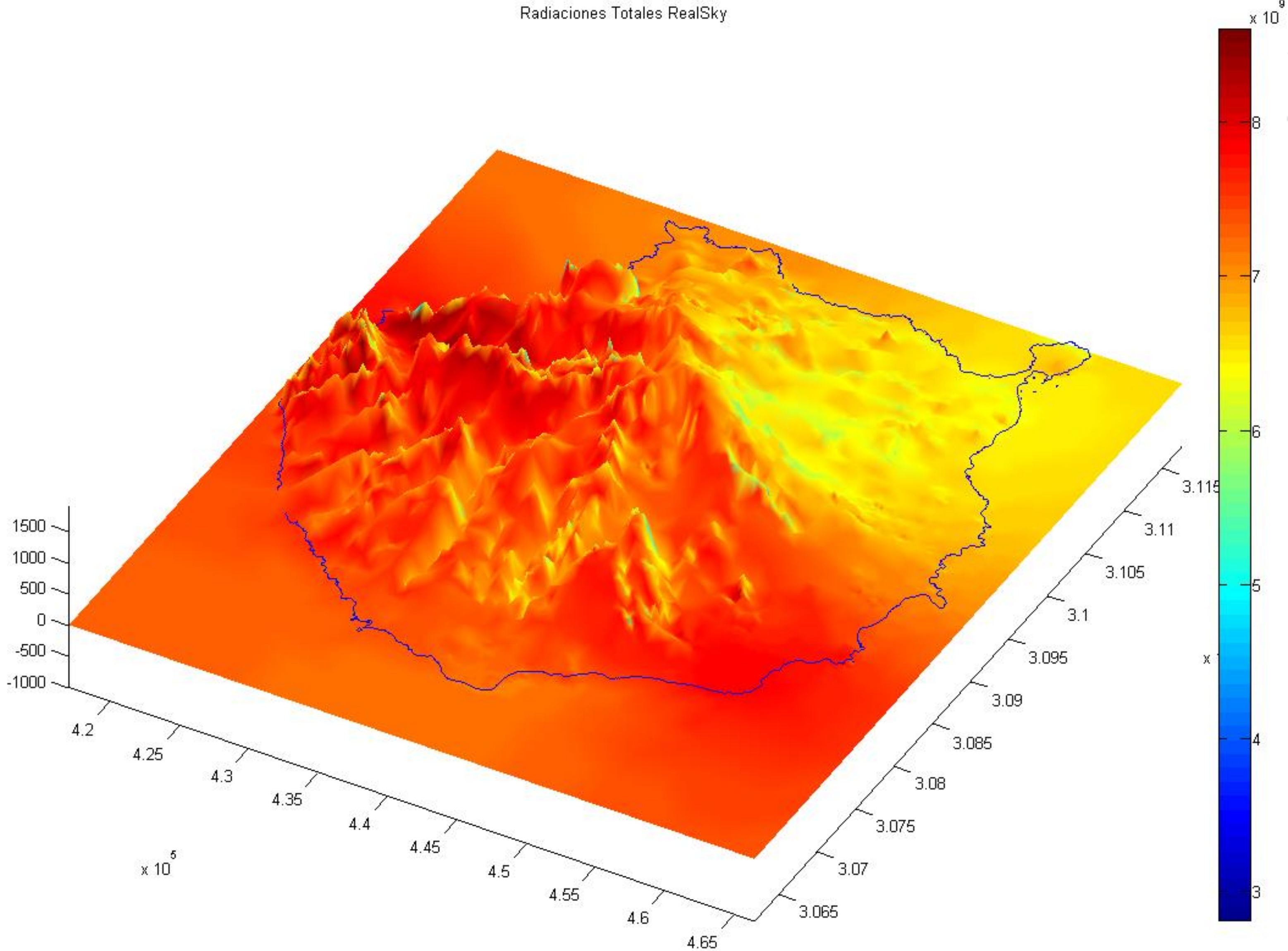
Influence of the trade winds:



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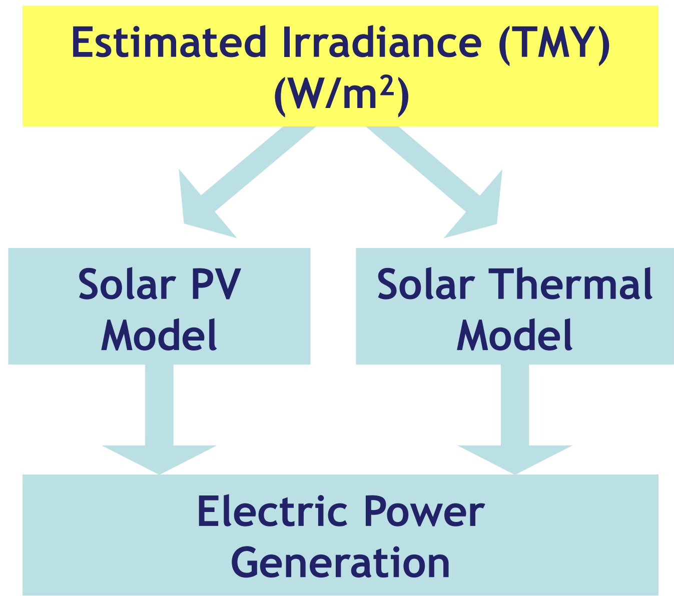
Results



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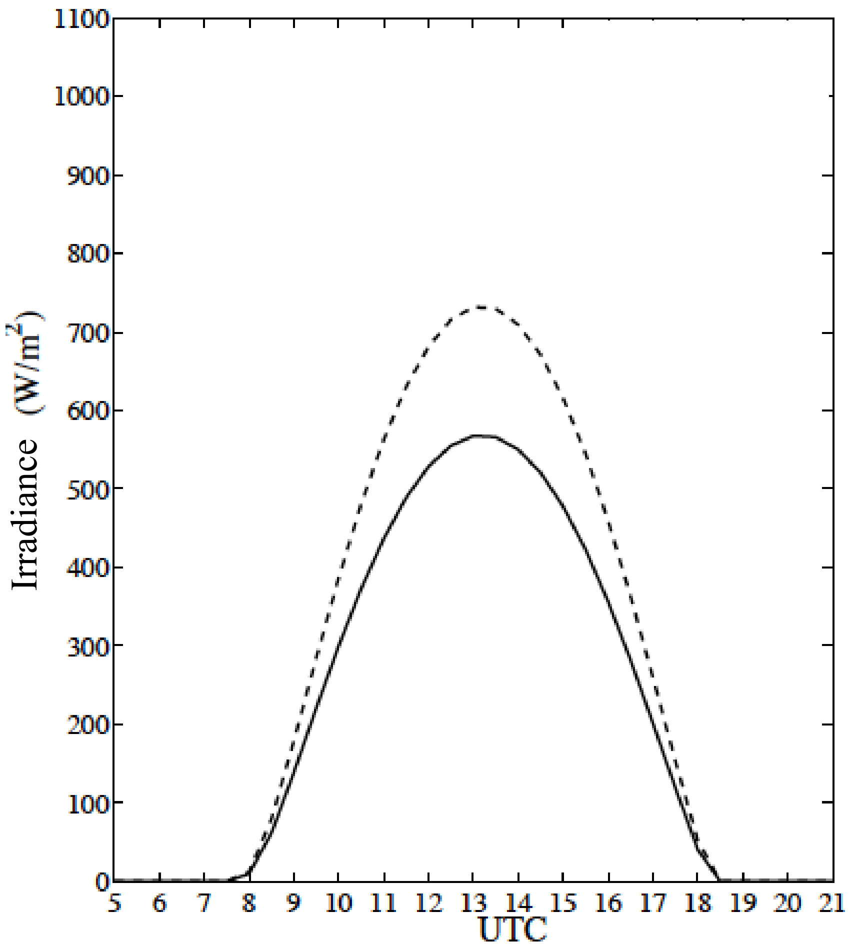
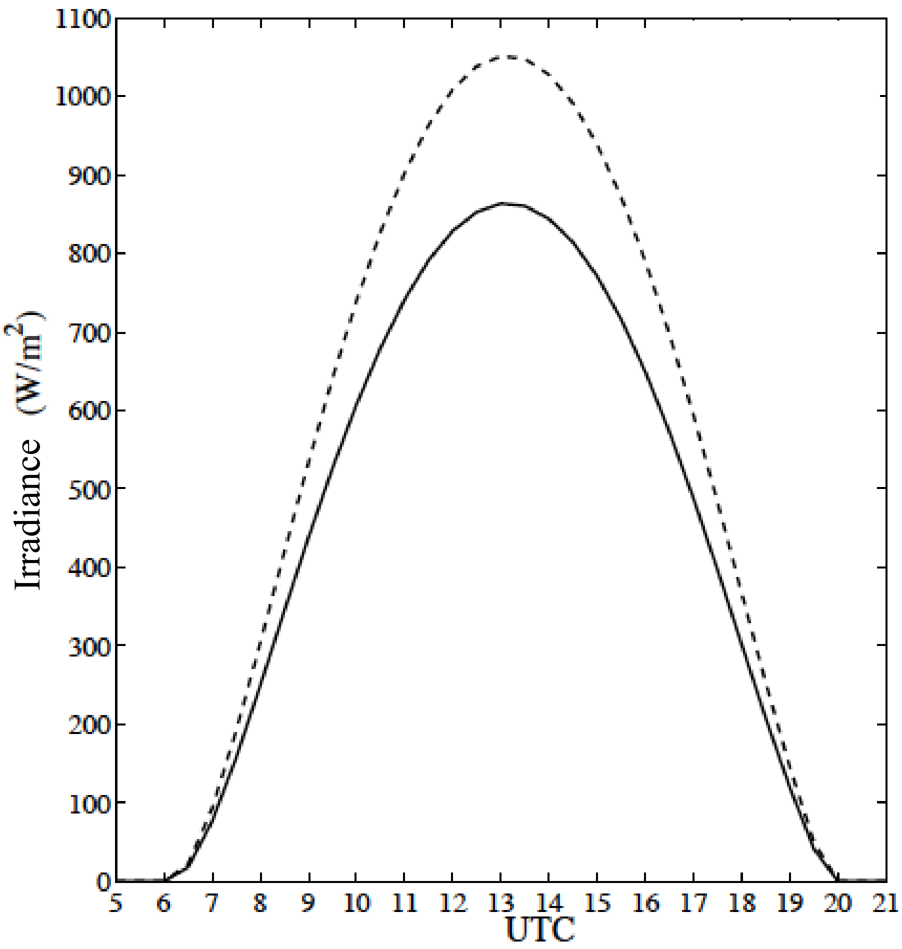
Results

Estimated Irradiance (TMY) (W/m^2)

January, 15th



July, 15th

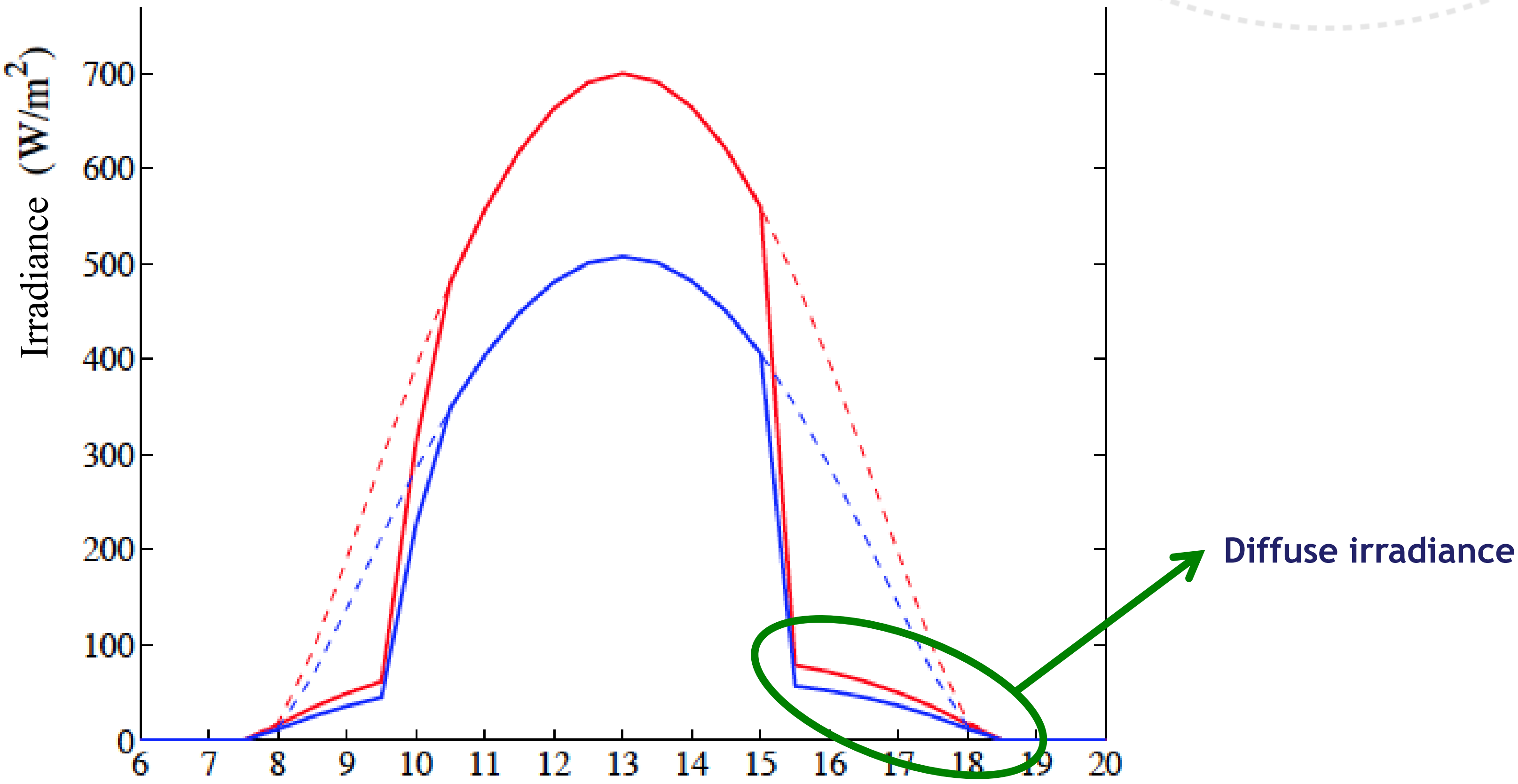


Maspalomas
Horizontal Surface

Results

Estimated Irradiance (TMY) (W/m²)

December, 21st



Shadowed triangle
Horizontal Surface

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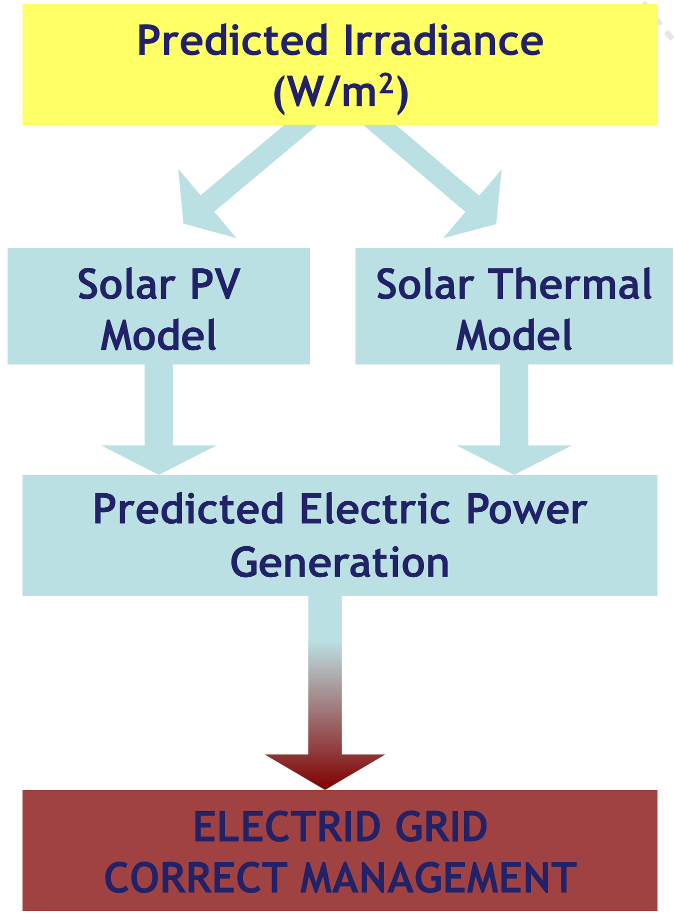
Results



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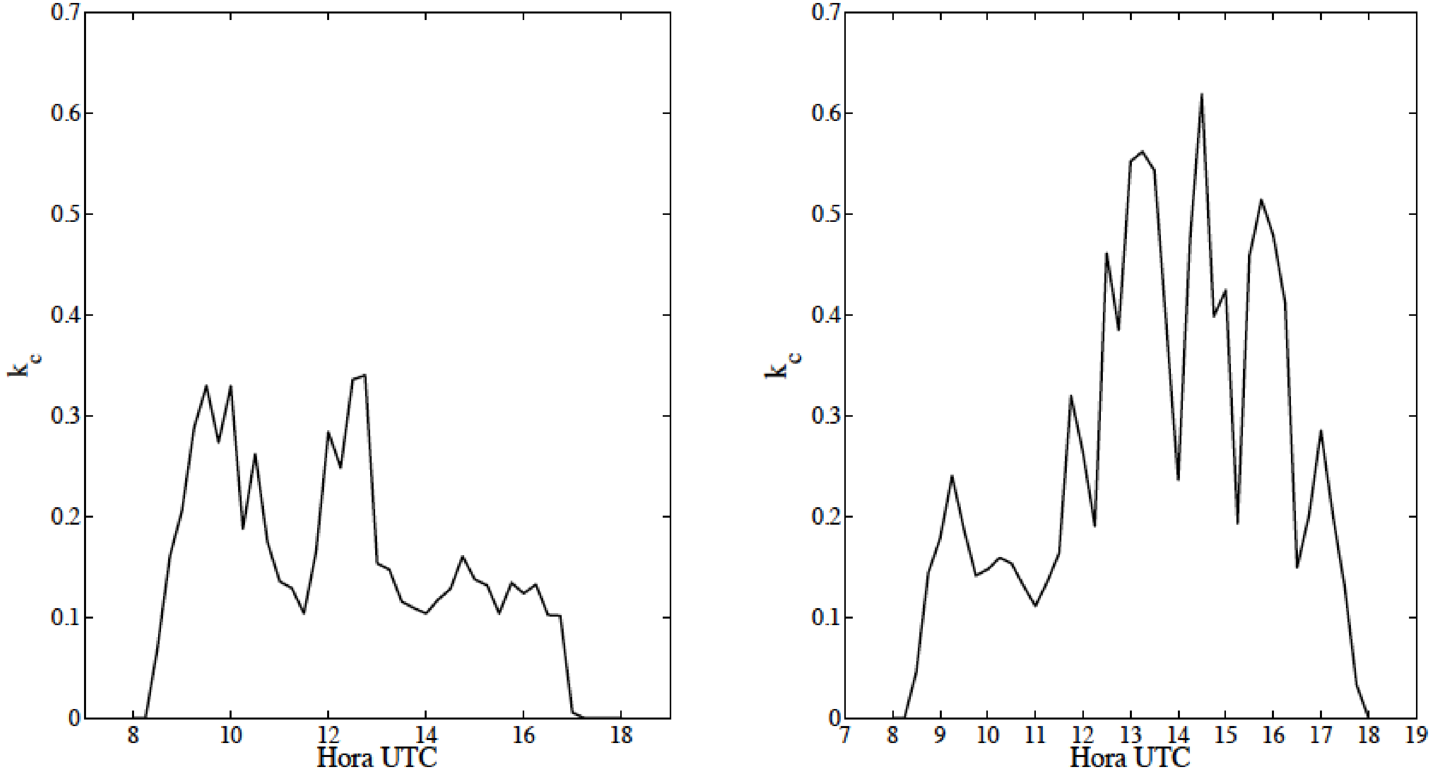
Predicted Irradiance (W/m^2)

Clear Sky Index Hourly Distribution



(a) Temisas (b) Lomo Carbonero

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December, 23rd 2009

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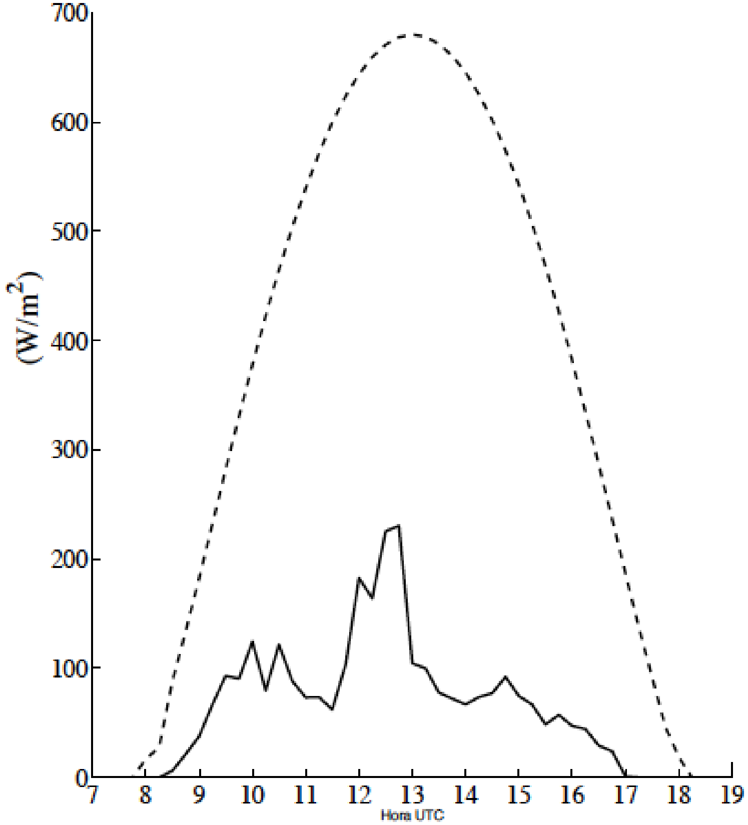
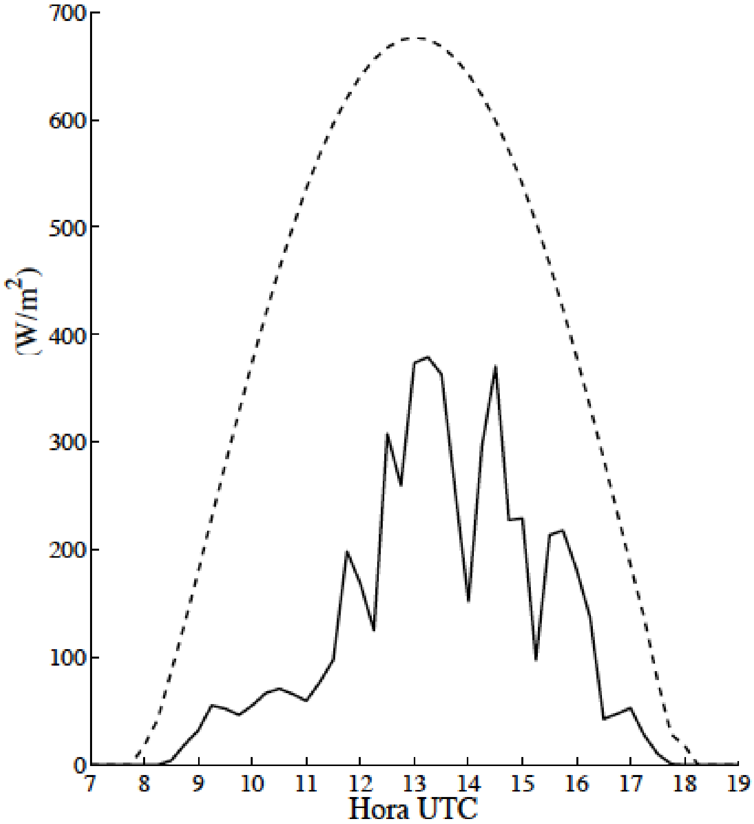
Predicted Irradiance
(W/m^2)



(a) Temisas



(b) Lomo Carbonero

December, 23rd
2009

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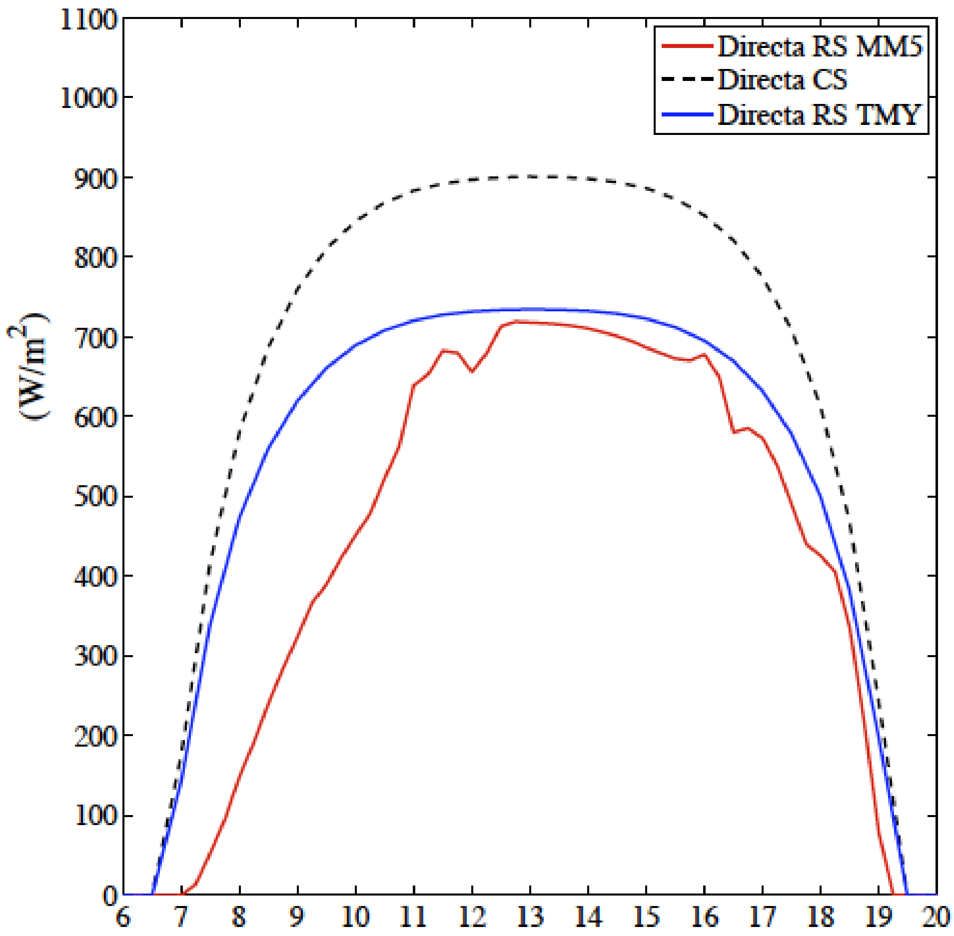
Results

Predicted Direct Irradiance (W/m²)



April, 10th

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Conclusions

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- 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
- Meteorological forecasting methods are very useful for developing a predictive solar radiation model
- The predictive model gives us realistic values about the solar radiation in the short term
- The predictive model allows to make a better management of the Power System

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Future research

- Improve the interpolation procedure of clear sky index
- Determinate the shadow boundary using ref/deref and mesh adaption by moving nodes
- Fully parallelization of the simulation
- Develop a predictive solar code based on artificial neural networks and compare results

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A New Predictive Solar Radiation Numerical Model

F. Díaz*, G. Montero, J.M. Escobar, E. Rodríguez, R. Montenegro

ESCO 2014, June 15-20 2014, Pilsen, Czech Republic

MEC - FEDER Project: CGL2011-29396-C03-01

http://www.dca.iusiani.ulpgc.es/proyecto2012-2014/html/

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