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Assessement of the method used to construct clearness index maps for the new European Solar Radiation Atlas ESRA

Hans Georg Beyer*[#], Gerhard Czeplak°, Uwe Terzenbach°, Lucien Wald*

*Groupe Télédétection et Modélisation, Centre d'Energétique Ecole des Mines de Paris, F-06904 Sophia Antipolis, France,

°Deutscher Wetterdienst, Klima und Umweltberatung Hamburg, D-22393 Hamburg, Germany,

[#]now at: Dept. of electrical engineering, Fachhochschule Magdeburg, D-39104 Magdeburg, Germany

Abstract

We present an assessement of the methods used to construct maps for a new Solar Radiation Atlas for Europe. For this atlas station data and satellite derived data are used in an interpolation/merging process to derive maps of the long term monthly global radiation that cover an area ranging from 30° W to 70° E and from 25° to 75° N. Our focus is on the discussion of the accuracy of the method applied - a co-kriging technique. Special emphasis is put on the discussion whether the use of satellite derived radiation maps with a low spatial resolution brings benefits.

1.Introduction

In the framework of the Joule Programme of the European Commission the project 'European Solar Radiation Atlas' (ESRA) aims to give a new data base on the solar resource in Europe and surrounding areas (Scharmer, 1994). The area of interest ranges from 30° West to 70° East and from 25° to 75° North. The subtasks of this project comprise the collection of radiation observations for the reference period 1981-1990, the setup of a toolbox to derive the radiation parameters of relevance for solar energy system design from the available data sets, and the construction of maps of monthly means for the whole area. In this paper we give an assesement of the method used to establish these radiation maps. The interpolation procedure applied to derive estimates of the radiation from both the set of station observations and additional radiation maps derived from satellite images is a co-kriging technique. A short introduction to this techique is given in an appendix.

The next section will give an overview of existing approaches for the construction of radiation maps. Section 3 and 4 present the input data sets and their preparation. The quality of the interpolation procedure is discussed in section 5. Special emphasis will be put on the discussion of the benefits of the use of the satellite maps available.

2.Methods applied for the interpolation of solar radiation fields

As the network of meteorological stations with a registration of solar radiation data is in general sparse, there had always been a need for interpolation procedures. The main techniques used are spline function based interpolations and various weighted average procedures comprising the kriging technique (see e.g. Journel and Huijbregts, 1978).

Spline functions are e.g. applied by Hutchinson et al. (1984) for the generation of maps of monthly mean irradiance over Australia and by Hulme *et al.* (1995) for the interpolation of long term (30 years) monthly means of sunshine duration data for Europe.

The application of different weighted average methods for daily radiation in Switzerland and various regions in the USA is discussed by Zelenka *et al.* (1992). Looking at the interpolation error, they reported only marginal differences between interpolations based on methods using weights according to the inverse squared distance for the neighboring stations and kriging methods. However from a general consideration of the methods it was concluded that the kriging technique is recommendable for the task of interpolation of radiation data from network stations. Further application of kriging methods for solar radiation fields are described by Zelenka and Lazic (1987) and Zelenka (1994). Kriging is also used for the generation of maps of the Meteonorm database for Switzerland (Kunz and Remund, 1995).

As discussed by Zelenka *et al.* (1992) the use of additional information on the solar radiation gained from the analysis of satellite images may improve the quality of radiation maps. This was proven both for daily and long term monthly mean data (D'Agostino and Zelenka, 1992; Zelenka, 1994). A co-kriging technique or simplified versions of it are recommended.
The work of Zelenka and his coauthors was mostly focussed on the area of Switzerland. In this special case they had to deal with a small region of considerable topographic complexity but with a very dense station network as compared to other countries. As satellite data are concerned they disposed of maps with a high spatial resolutin (pixel size of the maps approx. $10*10\ km^2$) .

For the task of the ESRA we have to deal with a largely increased area. The respective station grid that is very sparse in the outer region of the area of interest (see section 3). In addition satellite data that cover the whole region are only available at a low spatial resolution. Nevertheless, an application of the co-kriging procedure has been attempted. A sketch of this method is given in an appendix. For the application of the method of ordinary co-kriging as described in the appendix some pre-treatment of the data was necessary. These procedures, will be given in section 4.

3.Data base

Ground data

Ground data were made available for this project by the WMO radiation data center in St. Petersbourg, Russia and several national weather services..
Monthly means of the daily radiation sum H for 226 stations with global radiation measurements are computed from daily means covering the years 1981-1990 according to the criterion that at least 7 years of measured data are available for each station.
In addition a set of radiation data derived from daily means of sunshine duration data is taken into account. The derivation of the monthly mean of global irradiance from the sunshine duration data is based on Angstrom correlations and is described by Terzenbach (1996). This

set comprises data for 392 stations. Also data for 6 stations in Tunisia are extracted from a data base made available to us by the Joule Project 'SOLARGIS' (Vandenbergh, 1996). They stem from the period 1975-1984. Although this period diverges from the ESRA reference period these data are introduced to improve the final maps by imposing constraints on the estimates for northern Africa.

The total set of stations used is presented in the map shown in fig. 1. This map also gives the projection used for all maps involved in the calculation. Latitudes and longitudes form a rectangular grid. The size of a pixel on this map is 5'x5' (about 10 km x 10 km) giving a total map size of 600 x 1200 pixels.

As this ground data base is still quite sparse for latitudes lower than 35°, data for several countries in Africa and Asia are taken from a data base collected by the University of Massachusetts Lowell (Annonymous 1992): in total 39 stations for northern Africa and the middle east.. These data stem from time periods differing from the ESRA reference period and are of unconfirmed precision. Therefore they are applied only for a calculation of the latitudinal trend of the clearness index (see section 5) and are not taken into further consideration for the results presented here.

Satellite derived data

As satellite derived data, maps generated by the NASA-Langley Research Center are used. The data had been produced in the framework of the Solar Radiation Budget Project SRB (see e.g. Whitlock 1995, Di Pasquale and Whitlock 1995). This data set has only a low spatial resolution, but offers the advantage of an almost complete coverage of the ESRA region (for winter months data for northernmost latitudes are missing). Moreover this was the available data set with the best temporal coverage of the reference period.

Data for March 1985 to December 1988 are available. The original set with a pixel resolution of approx. 2.5###x 2.5###, is smoothed by a bicubic spline and re-mapped onto images with a resolution of 5' x 5' (Antoine, 1995). For the final calculations the 3-4 yearly maps available for one month are averaged. Fig. 2. presents the map for the month of June with radiation data transformed to clearness index values K ($K=H/H_{ext}$ with H_{ext} being the respective extraterrestrial radiation sum for the corresponding location). Due to the smoothing operation these maps show a continous variation in space (in constrast to the 2.5###x 2.5### resolution of the originla data base). However the spatial frequency of the variations remains low.

To assess the accuracy of the satellite derived data the clearness index values from monthly maps K_s are compared to the 10-years averaged ground data (more precise: mean monthly clearness index values K_g derived for the stations with at least 7 years of measured data) on a pixel to station basis. The rms-of relative error given by $\Delta = (K_s - K_g)/K_g$ is in the range of 8% (May) to 24% (January).

4.Data preparation and variogram estimation

The application of the ordinary kriging and co-kriging techniques as given in the appendix requires a field that is free of trends and isotropic. Therefore the data base presented above was pretreated to approach these conditions.

To remove the systematic variation of the irradiance data caused by the variation of the astronomic conditions all monthly irradiance data given as mean monthly radiation sum H are transformed into monthly clearness index values.

The clearness index is still affected by a trend with respect to the latitude. For both the ground data and the satellite data at the respective locations the mean clearness index values are extracted on a monthly bases using latitude classes of 3### width. In this calculation stations with an altitude greater then 1000m are not used. In doing this, the specific climatic contitions at mountain sites are not mixed with systematic trends due to pure latitude effects. An example for the month of August is given in fig. 3 for both the ground data and for the satellite derived values. This example shows that for the month presented the satellite data have an offset varying with the latitude.

To remove the latitudinal trend and the offset of the satellite data a simple correction is used:

$$\begin{aligned} K'_g(x_{lat,long}) &= K_g(x_{lat,long}) - K_{g,t}(lat) \\ K'_s(x_{lat,long}) &= K_s(x_{lat,long}) - K_{s,t}(lat) \end{aligned} \qquad (1)$$

where the trend functions $K_{g,t}(lat)$ and $K_{s,t}(lat)$ are empirically determined for each month by piecewise linerar interpolations of the data as given in fig.3.

As described in the appendix for the kriging and co-kriging procedure the spatial structure of the data field is presented by auto- ($\gamma^i(d)$) and cross-variograms $\gamma^{1,2}(d)$. For the trend corrected K' values the variograms are defined as:

$$\gamma^i(d) = \left\langle (K_i^{'}(x) - K_i^{'}(x+d))^2 \right\rangle$$

with $i : g, s$ (2)

$$\gamma^{g,s}(d) = \left\langle (K_g^{'}(x) - K_g^{'}(x+d)) \cdot (K_s^{'}(x) - K_s^{'}(x+d) \right\rangle$$

The variogram describes the expectation of the squared difference of the field values separated by a distance *d*. For an isotropic field the variogram should depend on the absolute value of *d* only.

As the spatial variation of radiation data is not only affected by the relative horizontal position of locations but also by the difference in altitude Zelenka and Lazic (1987) have proposed the use of an effective distance. The effective separation of locations is described by:

$$d_{eff} = \sqrt{d^2 + (\Delta h \cdot f)^2}$$

with:

d: horizontal distance (3)

Δh: difference in location altitude

f = relative scale factor: equivalent horizontal distance / vertical distance

While Zelenka and Lazic have set the factor *f* to *0.1 km/m*, we used a value of *0.3 km/m*. This was done on the basis of the results of cross-validation tests (see below) for both kriging and co-kriging procedure performed for various values of f (*0.1, 0.2, 0.3, 0.4* and *0.5 km/m*). Fig.4 shows the root mean square of relative errors calculated by the cross test as a function of f. In this calculation the full ground data set is involved. It can be seen that the smallest error is attained for the value of $f = 0.3$ *km/m*. It should be stressed however that the relative variation of the rms error with f is very weak: less than 5%, and that the results are only weakly dependent upon f. The figure also gives a first indication that the differences in the interpolation quality of kriging and co-kriging procedures are quite small. This will be discussed in more details in section 6.

The variograms used in the co-kriging are calculated thus for the detrended data K' and applying the effective distance d_{eff} according to eqn 2 with f set to *0.3 km/m*. The effect of the trend correction is shown in fig. 5. The variogram for uncorrected and corrected ground data has been analysed with respect to the orientation of the station separation. This was done by selecting only station pairs with differences of less than 3° either in latitude (station pairs with distance domminated by their east-west separation) or in longitude (station pairs with distance dominated by their north-south separation). Before the trend correction (i.e the variograms calculated for K_g), the differences of the variograms for north-south and east-west orientated station pairs are significant. For the trend corrected set both variograms are allmost identical. It may thus be concluded that the trend corrected field approaches isotropy. The effect of the use of the effective distance for the shape of the variograms is shown in fig.6. When applying the pure horizontal distance the variogram shows almost no decrease for small separation distances (below 200 km). This is caused by station pairs representing some valley/mountain combinations. The increase of the separation of these pairs induced by using the effective distance leads to a variogram with a more pronounced tendency to approach 0 for zero separation.

For the application of the procedure the variograms must be described by analytical functions. Here an exponential model is used, whose parameters a and b are fitted to the empirical variograms.

$$\gamma(d) = a(1 - \exp(-d / b)) \qquad (4)$$

The fit was performed on the samples calculated for the effective distance range of 0-1500 km with a class width of 50 km. Fig. 7 gives the auto- and cross-variograms for May. The auto-variograms indicate that, as expected, the detrended satellite data show less variance than the respective ground data. The ratio of the standard deviations is about 1.5. The cross-variogram reflects that the cross-correlation for detrended satellite and ground data for this month is about 0.5. For other months (January, February) this correlation decreases below 0.1. In the co-kriging technique the low correlation will results in the fact that the satellite data will have a small influence on the results only.

7.Application and results of the co-kriging

The data set as discussed above was used as basis for both kriging and co-kriging interpolations. Cross-tests are performed to estimate the quality of the interpolation and to judge the benefits of the use of the satellite data set.

To keep the expense in calculation time reasonable, the interpolation was performed by using the I = 25 closest stations at each location. An increase of the number of stations to 100 leads only to marginal differences in the results. In the co-kriging procedure, in addition to the I ground station values, $J = I+1$ satellite derived values are used. The satellite values are taken at the I pixels referring to the positions of the selected ground stations and the pixel referring to the location of interest.

A cross validation was performed in the following way. Each of the stations was for once removed from the data set and the corresponding interpolated value was calculated from the remaining set of stations. This procedure includes the removal of the station of interest from the calculation of the latitude means of the clearness index. However the variograms are not recalculated for every individual estimation. Thus the cross validation is not 'rigorous', but it is thought that the removal of one station would not affect the variogram models to a large extent.

In the following examples only the stations with at least 7 years of measured global radiation data (stations marked black in fig.1) are taken into account. Thus the results also reflect the effects of the use of irradiance data derived from sunshine duration data in the interpolation procedure.

The differences of the estimated clearness index values K^* as compared to the measured values of K_g are expressed in terms of the relative error:

$$\Delta = \frac{K^* - K_g}{K_g} \qquad (5)$$

For the basic test involving about 200 stations with at least 7 years of measured global radiation data the performances of the kriging and the co-kriging interpolation are almost identical. As shown in fig. 8 both methods result in a root mean square (rms) of the relative errors of about 0.08 in winter and of 0.05 in the summer months. An overall advantage of the co-kriging intepolation of about 2% may be deduced. In addition, the results for a gravity interpolation (see Appendix) are indicated. As already found by Zelenka *et al.* (1992) and Zelenka (1994) the loss of accuracy compared to kriging interpolation is only marginal (here: 4% with respect to the co-kriging results). The results for the gravity interpolation are derived using the 7 closest neighbors for all the stations. This value was found to give the lowest overall error for this technique. In general it may be stated that the performance of gravity interpolation is less even with respect to different regions and months than the results of the kriging procedures discussed in the following. These results are close to those found for spline interpolations of 30 year means of monthly sunshine duration data by Hulme *et al.* (1995) (rmse values of 10% in winter and 5% in summer).

Looking at selected groups of stations from areas with a high station density the differences of kriging and co-riging results are even more diminished (see fig. 9). The areas inspected refer to 47.5° < latitude < 55.0° and 6.0° East < longitude <15.0° East ('Germany') and a region including the main part of the Alps (45.5° < latitude < 48.0°; 6.0° East < longitude < 15.0° East). This result is obvious as the satellite data with their slow variation in space can bring no additional information to the field structure as presented by the sets of nearby neighbors. It should be noted, that for the region 'Germany' the precision of the interpolation is very high. The rms of the relative errors ranges from 0.06 (January) to below 0.03 (July). For the region 'Alps' the rms values are increased due to the complexity of the terrain. For the 20 sites inspected - which include 6 stations at altitudes above 1500m as well a the lowland site Milan (altitude = 20m) the rms values are in the range of 0.11 (January) to 0.05 (July).

The comparison looks different if stations are selected which show are large separation to the next neighbor. As example the cross test results for a set of all stations with a distance of more than 200 km to the next neighbor (8 - 13 stations, depending on the month) are shown in fig.10. Here the differences between the kriging and co-kriging results are more pronounced. The advantage of the co-kriging interpolation is visible for all months except November. The overall difference is about 9%.

A similar pattern arises for a test performed for all stations using an artificial restriction (fig. 11). As 'neighbors' for kriging and co-kriging only stations with a distance of more than 500 km to the site of interest are used. For the summer months, the rms of the relative errors for the co-kriging is about 6%. This values is close to the rms of the relative error describing the precision of the trend corrected satellite data for the respective month`s. From this we may conclude that for regions sparsely covered by ground stations even the low resolution satellite maps may add valuable information.

8. Conclusions

Monthly clearness index maps produced using the co-kriging interpolation described will be presented in the new European Solar radiation Atlas ESRA. Each map will give the monthly clearness index for each of the 1200 x 600 pixels of a 5´x 5´maps. The altitude values for the pixels are taken from a digital elevation model with the same spatial resolution.

Concerning this construction procedure some conclusion may be drawn. We think that the results presented here using the data base discussed, give an idea about the limits for interpolation methods for the whole region studied based on a common characterization of the spatial structure of the stochastic component of the field. Regional improvements may be possible by investigating the best method and structure representation for respective subsets of data.

Besides those regions with almost no ground station data, the most problematic regions are the mountaneous areas. Only for the Swiss alps the data network is dense enough to present some of the complex radiation field structure caused by this type of orographie. In reverse the orograpic structure will be recognizable in the irradiance maps. For this region however the Meteonorm maps (Kunz and Remund, 1995) are already available. This example uses a different procedure was applied to deal with the altitude dependance of the radiation field by assigning different altitude trend functions for as many as 11 separated subregions. As those functions have to be based on a small number of station data in each subregion and show considerable variation over the subregions this approach was not applied to the European Atlas. For all other high mountain areas the data base is not sufficient to represent detailed orographic effects. Again for the reason of diversity of altitude trend functions no 'ad hoc' altitude dependence is introduced here. Due to the use of the effective interstation distance single stations at higher elevations induce a weak dependance of the irradiances on the altitude for the surrounding regions. The respective data presented on the ESRA maps must be handled with care.

A major shortcoming for the preparation of radiation maps seems to be the lack of deterministic models linking orographic features, e.g. mountain ridges, with changes in the radiation field. Only few attemps in this direction are known to us. One is the empirical extraction of dependence on altitude as discussed above. Others include the test of using the distance from the shoreline as a characteristic site parameter in interpolation procedures or the empirical identification of climatic barriers decoupling sites on opposite sides of them (van der Voet *et al.* 1994). Establishing such empirical relationship requires a large station density for the whole region of interest. Alternatively, satellite derived maps with a high spatial resolution may be used as a data source to pin down systematic small scale variations.

It must be stated that in the present study the benefits due to the use of the available satellite derived maps are very limited. Obviously, due to their low resolution, they do not help to account for small scale orographic effects. As the overall correlation of satellite and ground data is not as good as expected, especially the uncertainty of the final maps for the winter month at the outer bounds of the inspected region is still in the range of 10-15 %.
Satellite derived maps from other sources have been taken into consideration. Maps prepared by the SUNSAT project (Raschke *et al.* 1991) having a resolution of about 50 km*50 km and covering the two years 1985 and 1986 have been tested. When detrended, the respective 2-year averaged monthly maps yield correlations with the 10 years ground data that are inferior to those calculated for the SRB maps. Here the variability of individual monthly radiation sums compared to the 10 years mean (see. e.g. Beyer *et al.* 1996) plays an important role. Using merged SRB and SUNSAT maps does not lead to any significant improvement of the co-kriging precision. To overcome these problems satellite derived maps with a reasonable spatial coverage and a suitable resolution must be available for the whole period of interest.

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Appendix

A short introduction to kriging and co-kriging techniques

Kriging was developed in the framework of geostatistics for the analysis of mineral ore resources (see e.g. Journel and Huijbregts, 1978). We will give a brief summary of the basic equations used in our application of these methods.

It is assumed that an estimate of the value of a field Y at a location x_o may be given by a linear combination of the field values measured at locations x_i (x representing the coordinates of a point).

$$Y^*(x_o) = \sum_i^I w_i Y(x_i) \qquad \text{(A1)}$$

In simple methods the weight w_i are set directly according to the distance d_{0i} between x_0 and x_i. For example the inverse squared distance methods (in the following also refered to as gravity interpolation) the weights are set as:

$$w_i = \frac{1}{d_{oi}^2} \cdot \frac{1}{\sum_j 1/d_{oj}^2} \qquad \text{(A2)}$$

The kriging procedure is based on the idea to select the weights w_i to give a minimum error of the estimator $Y^*(x_o)$ to the actual value $Y(x_o)$. This process requires information on the spatial structure of the field which is provided by the (auto-)variogram (or structure function).

$$\gamma(d) = \left\langle (Y(x) + Y(x+d))^2 \right\rangle \qquad \text{(A3)}$$

The variogram describes the expectation of the squared difference of the field values separated by a distance d. For simplicity we assume that the field is isotropic and thus that the variogram depends on the absolute value of d only. In practice this function may be estimated from a given data set by grouping station pairs in classes of distances and calculating the mean squared difference for each class. For the subsequent calculations the empirical variogram is in general fitted by analytical functions. The functions should reflect the expected characteristic of the variogram to increase with increasing distance *d*. An example for a model out of a family of suitable functions (see e.g. discussion in Zelenka *et al.*, 1992) later used in this study is given by:

$$\gamma(d) = a(1 - \exp(-d / b)) \qquad \text{(A4)}$$

Using the information on the variogram, minimizing the error of the estimates results in the following equations which determine the weight w_i if $Y^*(x_o)$ is to be estimated from a sample of *I* observations. Here the abreviated notation $\gamma(x_i, x_j) = \gamma(|x_i - x_j|)$ is used.

$$\begin{aligned} &\text{for } a = 1, I \\ &\sum_i^I w_i \gamma(x_a, x_i) + \mu = \gamma(x_o, x_a) \\ &\sum_i^I w_i = 1 \end{aligned} \qquad \text{(A5)}$$

μ: Lagrangian multiplier

The Lagrangian multiplier enters here to cope with the condition that the sum of the weights should be equal to 1, which assures that the estimate is bias free.

A additional source of information on the field may be given by data that are at least positively correlated with the studied field and sampled for a larger number of locations. In our context these are the radiation data estimated from satellite images. A tool for merging both information sources is given by co-kriging .

For the co-kriging procedure the cross-structure of two data fields is characterised by the cross-variogram of the different data sets.

$$\gamma^{1,2}(d) = \langle (Y_1(x) - Y_1(x+d)) \cdot (Y_2(x) - Y_2(x+d) \rangle \qquad \text{(A6)}$$

To estimate the cross-variogram the field data Y_1 and the additional data Y_2 must be co-sampled at a sufficiently large number of locations.

Using the information on the auto and cross-structure the interpolated value Y^* at location x_o may be derived from a weighted sum of I samples for Y_1 and J samples for Y_2 values where J should be larger than I.

$$Y_1^*(x_o) = \sum_i^I w_i Y_1(x_i) + \sum_j^J v_j Y_2(x_j) \qquad \text{(A7)}$$

The system of equations for the determination of the weights w_i and v_j using the auto (###[1],### [2])- and cross-variograms (###[1,2])is given by:

for $a \in \{1,\ldots I\}$

$$\sum_i^I w_i \gamma^1(x_a, x_i) + \sum_j^J v_j \gamma^{1,2}(x_a, x_j) + \mu_1 = \gamma^1(x_o, x_a)$$

for $b = 1, J$

$$\sum_i^I w_i \gamma^{1,2}(x_b, x_i) + \sum_j^J v_j \gamma^2(x_b, x_j) + \mu_2 = \gamma^{1,2}(x_o, x_b)$$

$$\sum_i^I w_i = 1$$

$$\sum_j^J v_j = 0$$

$\mu_{1,2}$: Lagrangian multipliers

(A8)

The last two equations again give the conditions for a bias free estimate.

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