Merging ground-measurements and satellite-derived data for the construction of global radiation map

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MERGING GROUND-BASED MEASUREMENTS AND SATELLITE-DERIVED DATA FOR THE CONSTRUCTION OF GLOBAL RADIATION MAPS

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ABSTRACT

The European Commission is realizing the first digital European solar radiation atlas of the Greater Europe. Climatological maps of the global radiation available at ground are to be constructed. For that purpose, radiation data have been collected which have been measured at about 300 meteorological ground stations. These stations are mostly located in Western Europe and therefore any interpolation technique applied to these data will provide poor results outside this area. Radiation maps derived from satellite images are used as a constraint to the interpolation procedure (kriging), though they are less accurate than the ground measurements. This study shows that, compared to an interpolation of the ground measurements alone, merging satellite-derived maps and ground-based measurements improves the assessment of the global radiation in any geographical location which is not a ground station, and peculiarly for those far from any ground station. The relative error is a whole lower than 10 % and decreases down to a few per cent when approaching a ground station.

1. INTRODUCTION

In the framework of the project "European Solar Radiation Atlas" (ESRA) maps of the global radiation impinging at ground should be constructed. They represent the monthly mean of daily sums of global radiation averaged over 10 years (1981 - 1990) for each geographical square of 5' of arc angle in size (*i.e.* about 10 km at 45° N). The area of interest ranges from 30° West to 70° East and from 25° North to 75° North. Measured values of irradiance sums or monthly sunshine hours are available for about 300 meteorological stations. This set of discrete values in space is used as a basis for the construction of the maps, which on the contrary can be seen as continuous in space. In addition irradiance maps derived from satellite images are used. They are called satellite maps hereafter for the sake of the simplicity. Such maps offer a rather poor accuracy compared to the ground-based measurements. Relative rms. is of order of 15 %. However, they describe quite well the spatial features of the irradiance. It is therefore thought that the information on relative differences of the irradiance at various sites as shown by the satellite maps may be fruitfully combined with the ground data. Merging both information may result in a final map that is more reliable than a map computed by an interpolation of the ground data alone. The basic idea is to calculate the differences of satellite derived data and ground data for the positions of the ground stations and to perform an interpolation to obtain a map of differences. The final maps are then computed by the addition of the map of differences to the original satellite map.

For an assessment of this idea it is necessary to check the quality of available satellite maps in view of this application. In the next section available satellite maps are described; their quality for the comparison with ground data is discussed. The following section briefly presents the variogram, which is the mathematical tool used to investigate and characterize the spatial structure of the solar radiation. It gives the bases for the interpolation method 'kriging' wich is applied here (the application of this technique for the interpolation of irradiance fields is described by e.g. Zelenka *et al.* 1992). The variograms of the ground stations measurements and of the field of deviations between the satellite maps and ground data are calculated and compared. The latitude trend, the anisotropy of the field and the effects of the difference in altitude are discussed. Finally a test is performed comparing the results of cross validations for kriging interpolations using either the fields of deviations as discussed above (*i.e.* merging ground data and satellite maps) or the ground data only.

2. Comparison of available satellite derived irradiance maps with ground measured data

The SRB (surface radiation experiment) set of satellite derived monthly irradiance maps is analyzed here. It covers the whole region of interest with a resolution of 2.5° x 2.5° (Anonymous 1994). It was derived in the framework of the earth radiation budget experiment (ERBE) and contains data for the years 1985-1988. The satellite data were processed with the method of Pinker and Ewing (1985) to provide irradiance. These satellite maps are projected onto a rectangular latitude/longitude grid. They are interpolated to a final resolution of (1/12)° by the means of a double cubic spline filter.

The ground data are taken from a collection prepared for the ESRA project. Data of daily global irradiance recorded in the period 1981-1990 at more than 300 stations are available. For the following comparisons only a subset of controlled quality used is. For each station more than 80% of the data for each individual month are available (measured and not suspected unreliable) for the 10 years. In the following all data (satellite and ground) are used in the normalized form of clearness index values, which characterizes the transparency of the atmospheric column over a pixel.

The comparison of the 4-year-averaged satellite maps with coincident ground data gives a root mean square error (rms) of 0.040 and a mean bias error (mbe.) of 0.016. The figures for the comparison with the 10-year-averaged ground data are a rms. of 0.041, and a mbe. of -0.021. From these results it may be concluded that the direct use of the satellite maps to predict the radiation for pixels with no ground data available would exhibit relative errors of about 10% for the monthly means. This gives one benchmark for the techniques of combining the ground and the satellite data. An other benchmark is given by the expected quality of a pure interpolation of ground data, which is now discussed.

3. Analysis of the experimental variograms

The experimental variogram is defined as:

$$\gamma(d) = \frac{1}{N_d} \sum_{i}^{N} \sum_{j=i+1}^{N} (X_i - X_j)^2 \cdot I(d_{ij})$$

with:

$$N_d = \sum_{i}^{N} \sum_{j=1+1}^{N} I(d_{ij})$$

$$I(d_{ij}) = \begin{cases} 1 \; if \, d - \delta < d_{ij} < d + \delta \\ 0 \; else \end{cases}$$

and d_{ij} : absolute distance between station i and station j

δ : half width of the distance classes applied (here 25 km)

For an interpretation of the variograms discussed below it should be mentioned that in general the lower the amplitude of the variogram, the more accurate the interpolation of the field.

In figure 1 the experimental variograms of the ground data (10 year average) and the deviations between the ground data and the 4-year-average SRB data are given. Here all pairs of stations and all month are used. The variogram for the ground data shows a remarkable increases for distances up 1500 km. The variograms of the deviations are almost flat, *i.e.* there is only a slight dependence on the interstation distance. For small distances the variogram of the deviations is almost identical to that of the ground data.

To understand the relation between the variogram of the ground data and those of the deviations one may examine the variogram of deviations of the satellite maps S from the ground data G. In a simplified notation this variogram is given by:

$$\gamma_g(d) = \left\langle [(S(x) - G(x)) - (S(x+d) - G(x+d))]^2 \right\rangle$$

with x presenting the coordinates of the data points.
This may be rewritten as:

$$\gamma_d(d) = \gamma_G(d) + \gamma_S(d) - 2\langle(S(x) - S(x+d) \cdot (G(x) - G(x+d))\rangle$$

The variogram of the deviations is the sum of the variogram for the ground data field and the satellite data field minus the co-variogram of the increments of both fields. Assuming that the mean of the increments is always zero ($\langle X(x) - X(x+d)\rangle = 0, X: S, G$) the notation:

$$\gamma_d(d) = \gamma_G(d) + \gamma_S(d) - 2r_{\Delta S, \Delta G}(d)\sqrt{\gamma_S(d)\gamma_G(d)}$$

may be used. $r_{\Delta S,\Delta G}(d)$ is the correlation of the increments. Using this equation one may conclude on prerequisites that $r_{\Delta S,\Delta G}$ must fulfill to keep the variogram of the deviations below the variogram of the initial field. If the ground and the satellite data have identical variograms the correlation must be at least 0.5 to obtain a lower variogram for the deviations. For distances smaller 200 km the correlations are well below 0.5. However as for these distances the variogram of the satellite data is considerably smaller than the variogram of the ground data, the variogram of the deviations for these distances is almost identical to that of the ground data.

4. Removal of latitude trend and of altitude effects

The almost constant increase of the variogram of the ground data can be tracked back to a trend with latitude which exists in the clearness index. This trend must be removed prior to the interpolation and then added to the interpolated map. This is done in the following way. The mean value of all clearness indexes in bands of latitude of 3° in width is calculated for both the ground and the satellite data. Then an interpolation between these sample values is performed which provides for each pixel the trend in latitude. Once the trend removed, the variogram of the ground data is almost flat for distances larger than 250 km. The de-trended data are called residuals of ground data and residuals of deviations.

The de-trending of the data set has an additional advantage. A detailed analysis shows that the variogram of the original data set varies with the orientation of the involved station pairs, *i.e.* the original data field is not isotropic. Once the trend correction applied the variograms for east-west and north-south orientated pairs are alike.

The additional curves in fig. 1 show that the qualitative relation of the ground field variogram and the variograms for the deviations remain unchanged after the de-trending whereby the quantitative differences especially at larger distances are sharply reduced (see the two lower curves). As the quantitative differences of the variograms for the residuals and the deviations of the residuals are now quite small, the question whether the interpolation of the deviations will really lead to an improvement as compared to the interpolation of the field of trend-corrected ground data is opened. This may be checked via cross tests.

Before performing the cross tests an additional topic is to be addressed: the effective distance of station pairs taking into account differences in station altitudes. The introduction of an effective distance is motivated by the fact that the variograms as those in fig. 1 show an 'irregular' behaviour at small distances. Within the ground data set, low-distance station pairs are mostly composed of stations at different altitudes (valley/mountain). It may be supposed that in general these pairs have the tendency to show higher squared differences than pairs of stations having the same altitude. Thus, following an idea of Zelenka and Lazic (1988) it seems reasonable to introduce an effective distance of stations pairs which takes into account both their horizontal separation and their difference in altitude. Since a difference in altitude *Dh* of some hundreds of meters leads to dissimilarities that are expected for horizontal separations *d* of some hundreds of kilometers the difference in altitude should be scaled appropriately. As an *ad hoc* definition of the effective distance d_{eff} the following relation may be used:

$$d_{eff} = \sqrt{d^2 + (\Delta h \cdot 1000)^2}$$

The performance of this additional correction is shown in fig.2 using the example for the data of one month. The variogram calculated with the use of the effective distance is close to that for station pairs with negligible altitude differences. Both have a clear tendency to approach zero for small distances.

5. Cross tests

In this section the performance of kriging interpolations using either the ground data alone or the field of deviations is checked. For this purpose the clearness index at a selected station is predicted from the ensemble formed by the other stations. The procedure comprises the following steps.

Firstly monthly variograms for the parameter under investigation (ground station data or deviations) are calculated using trend-corrected data (residuals) and employing the effective distance defined above. These experimental variograms are fitted by an analytical function. Secondly using the variogram model the kriging is performed for each station, taking into account the ten closest neighbors. As a model, a function of exponential type is used:

$$\gamma^2 = a \cdot \left(1 - exp(\frac{-d_{eff}}{b}) \right)$$

The two parameters *a* and *b* are determined *via* a least square fit to the experimental variograms for effective distances smaller than 1000 km. The quality of the fit may be judged from the figures.

Monthly rms. errors of the clearness index estimates for all stations are presented in fig. 3, where both the results for the interpolation of the residuals of the deviations and that of the residuals of the ground data are given. Comparing both results only small differences may be remarked. The annual mean of the rms. error is close to 0.029 for both data sets. The interpolation using deviations of satellite and ground data performs slightly better for the summer month whereas the interpolation of the ground data gives better results in winter. The last fact is a consequence of the reduced quality of the satellite derived irradiance data for situations governed by snow cover. As shown in fig. 4 this tendency gets clearer when the interpolation is not performed on the basis of the closest neighbor values but with stations separated by more than 500 km. The respective rms. errors give an assessment of the quality of the interpolation in regions with sparse ground data.

Normalizing the rms. errors given in fig. 3 with the monthly overall mean of the ground data leads to relative errors (relative rms.) of about 11% for January and 5% for July. The figures are similar to those reported by Hulme *et al.* (1995) for the interpolation of sunshine duration based on 800 stations in Europe.

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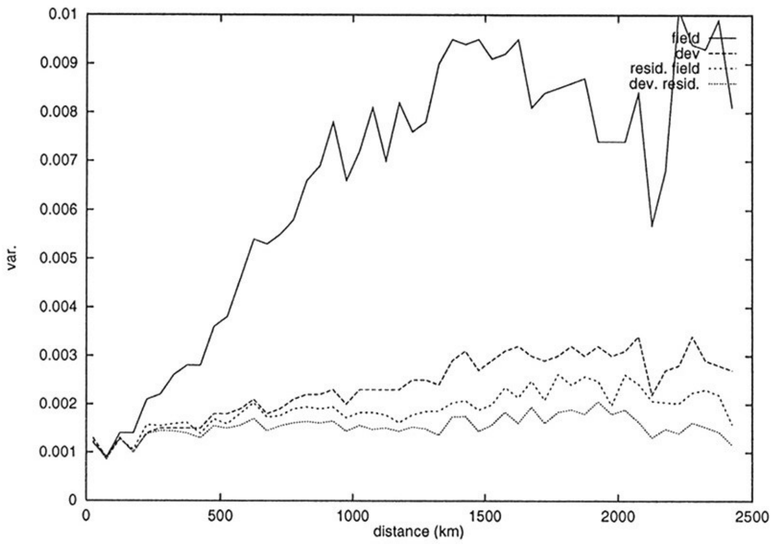

Fig. 1. Variograms for the original ground station field of 10-years averages of monthly clearness index values (solid line, «field») and for the deviations of the satellite data from these ground data, based on 4-years data from the SRB maps (dashed line, «dev»). The two dotted lines are obtained after a correction for a latitudinal trend is applied to the data. The upper one refers to the residuals of the ground data («resid. field»), the lower to the trend corrected deviations («dev. resid.»).

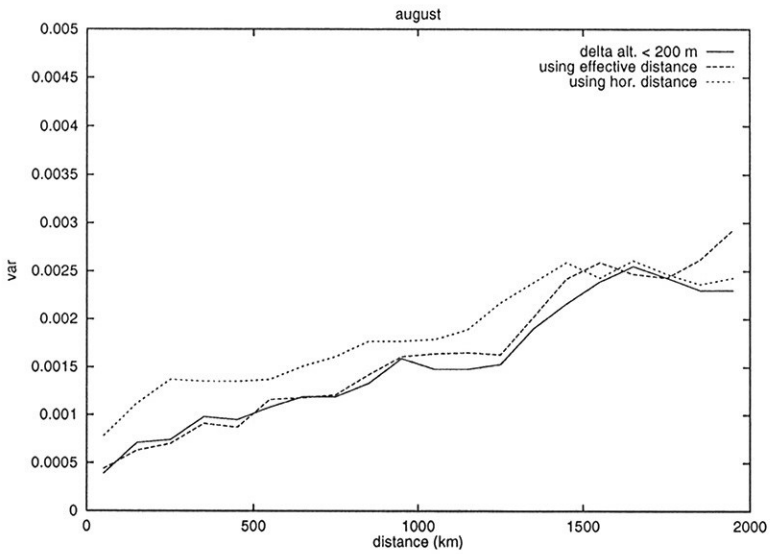

Fig. 2. Variograms of the deviations satellite - ground data based on trend corrected data. The solid line shows the variogram for station pairs with difference in altitude smaller than 200 m, the dotted line gives the variogram calculated for all stations pairs (upper line, «using hor. distance»). The third curves gives the variogram for all station pairs but analysed with respect to the effective distance discussed in the text. Data are for the month of August.

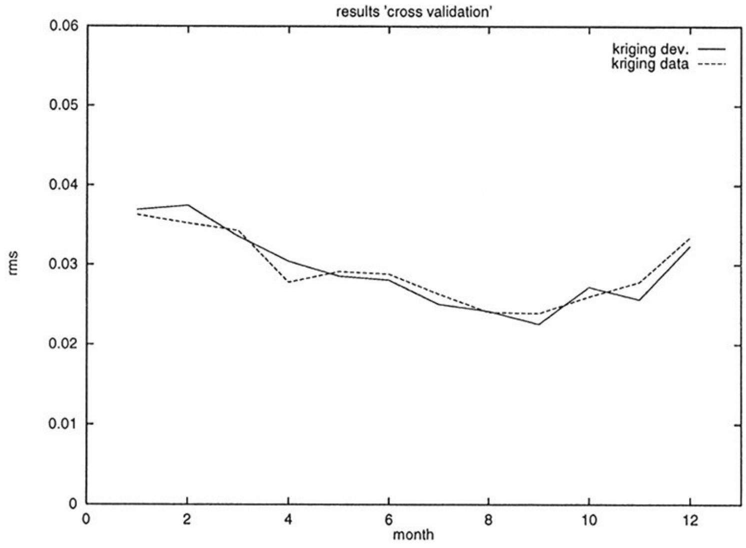

Fig. 3. Rms. errors for the cross validation. The curves give the monthly rms. for the kriging of the residuals of the deviations (full line) and for that of the residuals of the ground data.

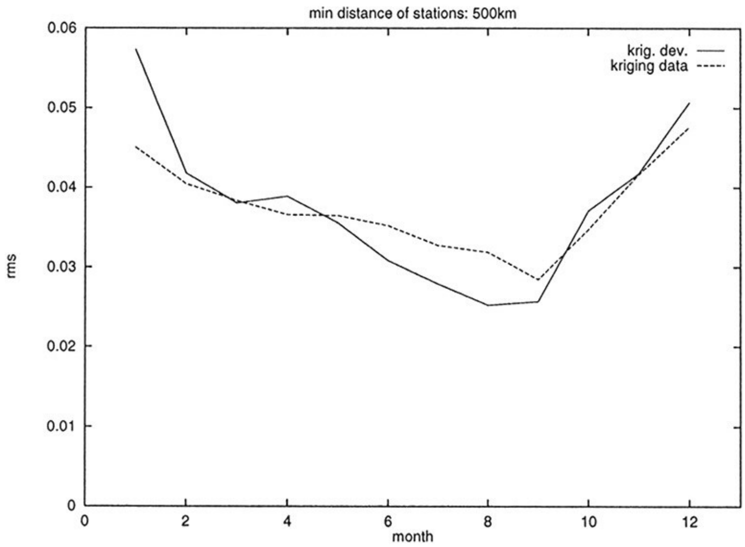

Fig. 4. Rms. errors for the cross validation using only stations separated by more than 500 km. The curves give the monthly rms. for the kriging of the residuals of the deviations (full line) and for that of the residuals of the ground data.