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Sunshine duration climate maps of Belgium and Luxembourg based on Meteosat and in-situ observations

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Abstract. Sunshine duration was historically the traditional parameter to quantify solar radiation. In the present study, we propose to benefit from the measurements made with Campbell-Stokes recorders at 18 sites in Belgium and Luxembourg to generate maps of daily sunshine duration for the period 1995–2005. In order to provide maps with the highest degree of confidence as possible, ancillary data of high spatial resolution derived from Meteosat satellites images are used within the mapping process. Different methods combining in situ sunshine duration measurements and Meteosat-derived data are evaluated. The best performing method is then used to compile a dataset of gridded daily sunshine duration data over Belgium and Luxembourg. The 1995–2005 sunshine duration climate map is finally provided. Various areal mean values are computed and discussed.

1 Introduction

Solar radiation was historically monitored by measuring the sunshine duration with Campbell-Stokes recorders. An estimate of the global solar radiation was then obtained through the well-known Ångström–Prescott equation (Ångström, 1924; Prescott, 1940). Although pyranometers are nowadays available to directly measure the global solar radiation, the sunshine duration is still an essential climatological parameter that is still monitored in many meteorological stations in order to extend the historical time series.

The Royal Meteorological Institute of Belgium (RMI) operates since the 50's a network of Campbell-Stokes recorders. This network has been complemented in the 90's with a network of automatic weather stations measuring the global solar radiation and, at a reduced number of sites, the sunshine duration according to the 120 $W m^{-2}$ WMO definition (WMO, 2008).

In this study, we propose to use these time series to generate daily maps of sunshine duration over Belgium and Luxembourg. Such a set of daily maps can be used for several purposes: for instance, to fill the gaps in the measurements time series, to estimate climatological normals, variability and extremes for specific locations as well as for areas (such as climatological or administrative regions, countries, etc.) and to derive climate maps.

Because the network of Campbell-Stokes recorders is relatively sparse (i.e., the network was deployed to a maximum of 18 sites over this area), interpolation errors can be high. Therefore, we aim at improving the confidence of the interpolation process by exploiting observations from the first generation of European geostationary meteorological satellites (i.e., the Meteosat First Generation (MFG) satellites) in addition to the in-situ measurements. In particular, the present analysis will rely on the Meteosat solar radiation climate data records released by the EUMETSAT Satellite Application Facility for Climate Monitoring (CM SAF). This dataset provides MFG-derived estimates of the global and direct solar radiations spatially distributed on the MFG field on view for the period 1983 to 2005 (Posselt et al., 2011). Because of a processing error in this dataset for the time period 1983 to 1994 (Journée et al., 2011), the present study is limited to the period 1995 to 2005, i.e., to 11 yr of data. It is important to note that an improved version of this MFG-based global solar radiation dataset has been recently proposed for the Benelux countries (i.e., Belgium, the Netherlands, and Luxembourg) by merging the satellite estimates with pyranometer measurements (Journée et al., 2012).

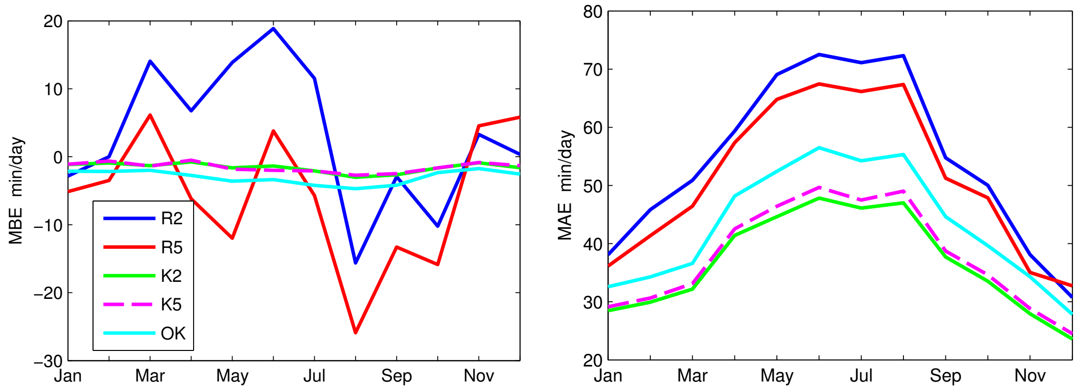

Figure 1. Cross-validation MBE (left panel) and MAE (right panel) for selected methods as a function of the month.

The main focus of this paper concerns the identification of the best way to combine the sunshine duration records with the MFG-derived solar radiation data. Several approaches are considered and evaluated in a cross-validation framework. The resulting dataset of daily spatially distributed sunshine duration data is then discussed, and sunshine duration climate maps over Belgium and Luxembourg are finally provided.

2 Solar radiation data

Two types of solar radiation data are considered in this study: in-situ daily sunshine duration time series acquired by Campbell-Stokes recorders and gridded daily solar radiation data derived from MFG observations.

Regarding the sunshine duration data, it should be noted that the network of Campbell-Stokes recorders has slightly varied over the period 1995–2005: the number of sites has changed from 15 sites in 1995 to 17 sites in 2005, with a maximum of 18 sites in 2000. Missing data are occasionally reported. A few additional sites are measuring the sunshine duration by means of automatic sensors. These data are not considered here in order to avoid spatial heterogeneities due to different measurement instruments. The location of the 18 Campbell-Stokes recorders is illustrated on Fig. 1.

Gridded solar radiation data were extracted from the Meteosat solar radiation climate data records released by the EUMETSAT Satellite Application Facility for Climate Monitoring (CM SAF), which provides MFG-derived estimates of the global and direct solar radiation (Posselt et al., 2011). This dataset was generated by an adaptation of the well-known Heliosat method (Cano et al., 1986; Rigollier et al., 2004), which determines the effective cloud albedo (or cloud index) from the reflectance measured by the broadband visible channel of MFG. The effective cloud albedo enables the all-sky global and direct irradiances to be estimated through the use of models that simulate the solar irradiances in clear sky conditions. The CM SAF dataset currently covers the period 1983 to 2005 and is provided on a regular $0.03° \times 0.03°$ latitude-longitude grid after triangulation regridding from the original MFG grid, which has a spatial resolution of 2.5 km at sub-satellite point. As previously mentioned, the present study is restricted to the period 1995 to 2005 (i.e., 11 yr of data). Regarding global solar radiation, a composite dataset based on the CM SAF data and pyranometer measurements made in the Benelux countries was shown to be significantly more accurate than the original CM SAF data as well as gridded datasets based on spatially interpolated in-situ measurements (Journée et al., 2012). In this study, both the CM SAF data (providing daily global and direct solar radiations) and the composite dataset (providing the daily global solar radiation) are considered.

3 Data merging approaches

Several approaches can be considered to combine two types of solar radiation data in order to generate daily sunshine duration maps with the highest degree of confidence. Two methods will be investigated here.

First, the Ångström–Prescott equation provides a linear relationship between the relative sunshine duration (i.e., the sunshine duration, SD, normalized by the maximum possible sunshine duration, $\mathrm{SD_{max}}$) and the clearness index (i.e., the global horizontal solar radiation, G, normalized by the extra-atmospheric radiation, E), i.e.,

$$\frac{\mathrm{SD}}{\mathrm{SD_{max}}} = a + b\frac{G}{E}. \qquad (1)$$

The site-dependent coefficients a and b can be estimated at each sunshine duration measurement site, and then spatially interpolated at the same spatial resolution as the ancillary global solar radiation dataset. Equation (1) is finally applied to each grid point to generate daily sunshine duration maps. The same approach can be considered for further regression models that estimate the relative sunshine duration based on the beam ratio B/G, where B is the beam horizontal solar radiation (Journée and Bertrand, 2011a), e.g.,

$$\frac{\mathrm{SD}}{\mathrm{SD}_{\mathrm{max}}} = a + b\frac{B}{G}. \tag{2}$$

The clearness index and the beam ratio can also be combined within the same regression model,

$$\frac{\mathrm{SD}}{\mathrm{SD}_{\mathrm{max}}} = a + b\frac{G}{E} + c\frac{B}{G}. \tag{3}$$

A second method consists in the use of geostatistical techniques, such as kriging with external drift (KED), that are able to handle densely sampled ancillary variables highly correlated with the parameter of interest (Wackernagel, 1995). In the context of relative sunshine durations, KED can be used with either the clearness index or the beam ratio as a drift, or simultaneously with two drifts.

4 Cross-validation analysis

The three variants of the two merging approaches are validated by leave-one-out cross-validation based on the 18 sunshine duration measurement sites and compared against the ordinary kriging (OK) spatial interpolation of the in-situ measurements. Regarding the linear regression models, this means that the coefficients a, b and c at one of the sites are successively spatially interpolated by ordinary kriging from the coefficients at the other sites. For the kriging-based methods, the measurement at one of the sites is successively omitted in the merging/interpolation process. In this way, the estimation at a specific site is independent of the measurements made at that site, which can thus be used to evaluate the quality of the estimation. The following statistics are provided in Table 1:

– the cross-validation mean bias error

$$\mathrm{MBE} = \frac{1}{n}\sum_{k=1}^{n}(\overline{\mathrm{SD}}_k - \mathrm{SD}_k),$$

– the cross-validation mean absolute error

$$\mathrm{MAE} = \frac{1}{n}\sum_{k=1}^{n}|\overline{\mathrm{SD}}_k - \mathrm{SD}_k|,$$

where SD_k is the measured daily sunshine duration and $\overline{\mathrm{SD}}_k$ is the corresponding estimation. The summation is done on all daily instances from 1995 to 2005 and all stations with available in-situ measurements. Regarding ancillary information on global solar radiation, both the CM SAF data (denoted by G in Table 1) and the composite dataset (denoted by $\overline{G}$ in Table 1) are considered. Because of the limited number of measurement sites, the variogram used by OK and KED to model the spatial correlation of the relative sunshine duration is not estimated on a daily basis but kept constant on the entire validation period. Based on Journée and Bertrand (2011b), we used an exponential variogram model with zero nugget and a range fixed to 300 km and 150 km for OK and KED, respectively.

Table 1. Cross validation mean bias error (MBE) and mean absolute error (MAE) in minutes per day. G and $\overline{G}$ denote the solar radiation data from the CM SAF data and the composite dataset, respectively.

Method		MBE	MAE
R1	Regression model (1) based on G/E	−1.51	59.1
R2	Regression model (1) based on $\overline{G}/E$	3.09	54.5
R3	Regression model (2) based on B/G	3.41	63.3
R4	Regression model (3) based on G/E and B/G	−5.25	55.7
R5	Regression model (3) based on $\overline{G}/E$ and $B/\overline{G}$	−5.66	51.2
K1	KED with G/E as drift	−1.50	37.6
K2	KED with $\overline{G}/E$ as drift	−1.59	36.7
K3	KED with B/G as drift	−1.34	37.6
K4	KED with G/E and B/G as drifts	−1.27	38.9
K5	KED with $\overline{G}/E$ and $B/\overline{G}$ as drifts	−1.55	37.9
OK	Ordinary kriging (spatial interpolation)	−2.98	43.1

The results in Table 1 indicate that the best performance is obtained with KED. The sensitivity to the different considered drifts is rather low. The smallest MAE is however reached when the clearness index is used as a drift and information on the global solar radiation is taken from the in-situ/MFG composite gridded dataset. Surprisingly, the simple spatial interpolation of the in-situ sunshine duration measurements outperforms the use of linear regression models. A possible reason for this is that, in contrast to the linear regression models, the kriging methods used with zero-nugget variograms perform an exact interpolation, i.e., estimations at measurement sites equal the measurements. Regarding the linear regression models, the best performance in terms of MAE is achieved when three parameters need to be fitted and when global solar radiation data is taken from the composite dataset.

The seasonal variability of the cross-validation indices is illustrated in Fig. 1. While the kriging-based methods exhibit a small MBE all the year around, the MBE of the linear regression models is very variable from month to month. This has to be related to the regression coefficients that are fixed to constant values over the entire period 1995–2005 and not fitted independently for each month. Regarding the MAE, the highest errors are observed in summer for all methods, i.e., when the daily sunshine duration can reach high values.

In Fig. 2, the cross-validation MAE of the regression model R2 and the kriging approach K2 are computed separately for each station and spatially interpolated by OK. For both methods, the MAE is the highest for isolated stations (e.g., in Luxembourg) and the smallest in densely covered regions (e.g., center area of Belgium). The difference between these two error maps (Fig. 2, right panel) indicates that the

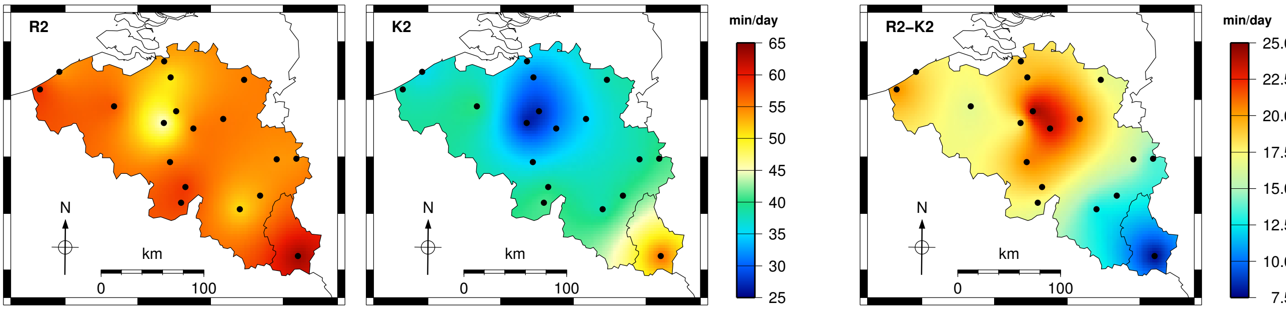

Figure 2. Spatial distributions of the cross-validation MAE for the methods R2 (left panel) and K2 (center panel), and spatial distribution of their difference (right panel).

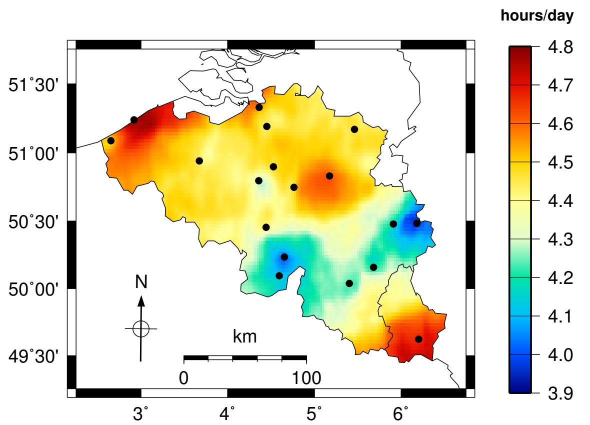

Figure 3. 1995–2005 mean map of the daily sunshine duration.

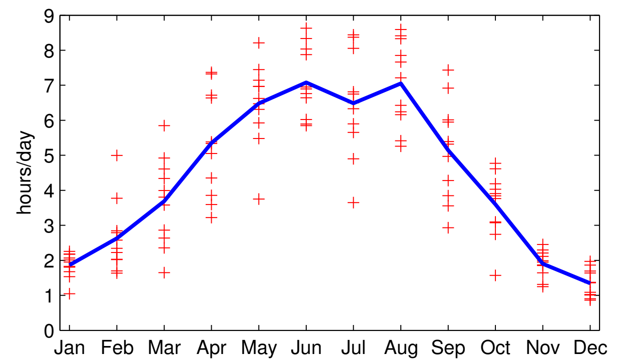

Figure 4. 1995–2005 monthly means (red dots) and monthly normals (blue line) of the daily sunshine duration spatially averaged over Belgium and Luxembourg.

benefits of K2 versus R2 is the highest for densely covered areas and the smallest for sparsely covered areas. For both methods, but especially for K2, the access to daily sunshine durations from neighboring countries' stations located in the border area would be highly valuable.

5 Sunshine duration climate maps

In view of the results discussed in Sect. 4, the KED method with the clearness index based on the in-situ/MFG composite dataset as a drift (i.e., K2) was used to generate maps of the daily sunshine duration on a regular latitude-longitude grid of resolution $0.03° \times 0.03°$. In order to deal with missing sunshine duration data as well as with the varying number of sunshine duration measurement sites, such maps are computed on a daily basis in order to generate a complete time series over the period 1995–2005.

Several outputs dedicated to climate analysis can be extracted from such a gridded database of daily data. First, the 1995–2005 sunshine duration climate map of Belgium and Luxembourg was computed by taking the average of all the daily maps. As shown in Fig. 3, the largest values are observed over the Belgian coastline and the South of Luxembourg, while the smallest ones are observed around the highest point of Belgium, in the plateau of the Hautes Fagnes. This distribution has many similarities with the distribution of the global solar radiation (Journée et al., 2012), which is largely dominated by clouds. On average over Belgium and Luxembourg, the mean daily sunshine duration amounts to 4 h and 24 min.

The generated database allows also to compute monthly mean values at the scale of a country through the computation of areal means. As shown in Fig. 4, the daily mean sunshine duration is the largest in June and August. Regarding the month of July, the sunshine duration was very variable over the period 1995–2005 (from 03:40 per day in July 2000 to 08:26 per day in July 2003).

Finally, we illustrate in Fig. 5 the time series of the daily sunshine duration spatially averaged over Belgium and Luxembourg. A one-year moving window averaging has been performed in order to analyse the annual variability. On a yearly basis, the smallest and largest sunshine duration values were observed in 1998 and 2003, respectively. No significant trend was detected.

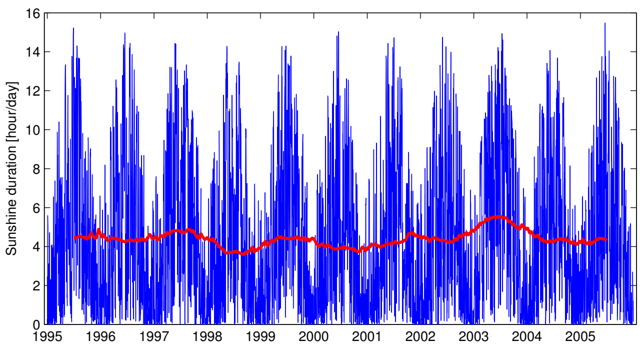

Figure 5. Time series of the daily sunshine duration spatially averaged over Belgium and Luxembourg (blue curve) and the corresponding one-year moving window average (red curve).

6 Conclusions

In this study, a time series of daily sunshine duration maps was compiled for Belgium and Luxembourg by combining in-situ sunshine duration measurements with high resolution ancillary data derived from Meteosat First Generation (MFG) satellites images. Two classes of methods to combine the two data types were compared: linear regression models, such as the well-known Ångström–Prescott equation, as well as geostatistical interpolation techniques such as kriging with external drift (KED). The cross-validation analysis indicated that the KED method outperforms the linear regression models. KED was tested with various ancillary data as drift: the clearness index, the beam ratio as well as both of them. Although the sensitivity to the type of drift is rather low, the best performance is obtained by using only the clearness index as drift and extracting information on global solar radiation from the in-situ/MFG composite dataset. The 1995–2005 sunshine duration climate map of Belgium and Luxembourg was finally proposed. The sunshine duration is the highest in the coastal area as well as in the South of Luxembourg. Monthly mean values were computed for Belgium and Luxembourg, and the annual variability was analyzed. No significant trend in the daily sunshine duration was found for the period 1995–2005 over Belgium and Luxembourg.

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