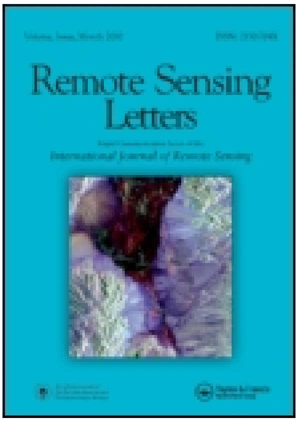

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Sensitivity to spatio-temporal resolution of satellite-derived daily surface solar irradiation

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Solar radiation data are essential for many applications, and in particular for solar energy systems. Because ground-based measurements of solar radiation are usually scarce, several methods have been proposed to estimate the solar radiation incoming on a horizontal surface at ground level from satellite imagery. These satellite-based estimations can be used as such, or combined with ground-based measurements. Because the satellite data sets differ in spatial and temporal resolution, this study evaluates the sensitivity of the satellite-derived daily surface solar irradiation to the underlying space and time resolution. More precisely, three surface solar radiation data sets retrieved from the Meteosat Second Generation (MSG) satellites are compared against ground-based measurements. Additionally, the benefit of merging information from the ground-based measurements with satellite data is explored. The study finds that the accuracy of daily surface solar irradiation estimates increases by up to 10% by doubling the temporal resolution of the MSG data, while it is largely insensitive to spatial resolution. This suggests that future geostationary satellite missions might primarily improve temporal rather than spatial resolution.

1. Introduction

The strong increase in the utilization of solar energy technologies such as photovoltaic and solar thermal power plants, passive solar heating/cooling systems and daylighting systems in buildings makes the availability of reliable solar radiation data important. Traditionally, solar radiation is observed with ground-based meteorological station networks. Since installation and maintenance costs of such networks are high, they are not very dense in most regions of our planet. Consequently the spatial coverage of solar radiation data is inadequate for many applications. The lack of information frequently results in an incorrect system sizing, non-optimum site selection, unreliable system performance or unnecessary use of conventional energy sources (e.g. Colle *et al.* 2001).

To complement the sparse network of surface measurements, numerous algorithms have been developed to estimate the surface solar irradiance (SSI) from satellite radiances (see e.g. Cano *et al.* (1986), Schmetz (1989), Pinker *et al.* (1995), Zelenka *et al.* (1999), Perez *et al.* (2002)).

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Due to the high variability of clouds and radiation, the small number of overpasses of polar orbiting satellite systems has so far limited the adoption of such satellite data in solar radiation monitoring applications. Since the early 1980s, the first generation of European meteorological geostationary satellites (Meteosat) was successfully used in the context of solar energy assessment (Hammer *et al*. 2003, Lefèvre *et al*. 2007). The enhanced capabilities of the Meteosat Second Generation (MSG) satellite provides the potential to extend the applications for satellite-derived solar surface irradiance. Satellite data for Europe and Africa are now available at high spatial, spectral and temporal resolution to continuously monitor the physical properties of clouds, and to quantify their influence on solar radiation. Recently, Journée and Bertrand (2010) demonstrated the benefit of merging ground-measured and MSG-derived SSI values to provide reliable high-resolution solar radiation data over Belgium. Leave-one-out cross-validations (CVs) indicate that merged data is systematically more accurate than each data source taken separately. The dominant information with which the satellite-retrieved data sets contribute to the merged data is the spatial distribution of SSI which in Belgium is largely dominated by clouds.

In contrast to ground measurements that are time-integrated values for pinpoint locations, satellite information is an instantaneous snapshot over a large area. In this study, we have therefore conducted a series of sensitivity analyses to determine to what extent the spatio-temporal resolution at which the SSI values are retrieved from MSG data may influence the accuracy of the merged daily surface solar irradiation estimates. Three different algorithms to retrieve SSI values from MSG data at various temporal and spatial resolution have been considered as well as SSI measurements performed at 13 radiometric stations operated by the Royal Meteorological Institute of Belgium (RMIB).

2. MSG-derived surface solar irradiance

MSG is the current generation of European geostationary meteorological satellites (Schmetz *et al*. 2002). The Spinning Enhanced Visible and Infrared Imager (SEVIRI) imaging radiometer onboard MSG has a 15-min repeat cycle and observes the Earth-atmosphere system with a spatial sampling distance of 1 km (High-resolution visible (HRV) channel) to 3 km (spectral channels) at the subsatellite point. The spatial resolution of the SEVIRI spectral channels (HRV channel) degrades to about 6 km (resp. 2 km) in the North–South direction and 3.3 km (1.1 km) in the East–West direction above Belgium.

Different methods exist to derive SSI from satellite data. The first two algorithms considered in this study relate top of atmosphere-reflected radiation flux density to SSI. Both were developed in the framework of the Eumetsat Satellite Application Facility (SAF) network. The algorithm developed by the Land Surface Analysis Satellite Application Facility (LSA SAF, landsaf.meteo.pt) retrieves the SSI from MSG images by means of simplified radiative transfer equations (Geiger *et al*. 2008). The method makes use of different parameterization schemes for clear and cloudy sky conditions. The algorithm of the Satellite Application Facility on Climate Monitoring (CM SAF, www.cmsaf.eu) uses look-up tables (LUTs) based on pre-computed radiative transfer model results for the retrieval of SSI (Müller *et al*. 2009). Two distinct LUTs are used, one for clear sky and one for cloudy sky situations, respectively.

The third method uses normalized reflectance measurements to determine the cloud transmission or cloud index. A clear sky model is used afterwards to calculate the SSI based on the retrieved cloud index. This approach, known as the Heliosat method, was initially developed for Meteosat First Generation satellites (Cano *et al*. 1986, Beyer *et al*. 1996, Hammer *et al*. 2003, Rigollier *et al*. 2004), and later adapted to MSG by taking advantage of its higher spectral, spatial and temporal resolutions (Dürr and Zelenka 2009). In this study, an upgraded version of the Dürr and Zelenka (2009) algorithm was run over a spatial domain ranging from 49.0° N to 51.5° N in latitude and from 2.75° W to 6.5° W in longitude in order to generate SSI data over Belgium at the MSG HRV channel spatial resolution. Because the original HRV geolocation performed by the EUMETSAT ground segment is only accurate up to ±3 HRV pixels, a watermask-based georeferencing procedure has been applied to the MSG HRV images. The best long-term match was observed for shifts of –2 horizontal and –1 vertical pixels.

In addition to the differences in retrieval methods, the MSG-derived SSI values used in this study also differ in the spatial and temporal resolutions at which they have been delivered. The LSA SAF estimates are generated every 30 minutes and are distributed to the users in near real-time at the SEVIRI spectral channel resolution. While the CM SAF retrievals are performed on a hourly basis at the SEVIRI spectral channel resolution, the operational CM SAF product is provided on a 15 km × 15 km sinusoidal grid in daily average. Because the resolutions in time and space of the operational CM SAF product are relatively coarse, intermediate values were considered in the present study, namely instantaneous hourly SSI values remapped onto a 3 km × 3 km latitude–longitude grid [R. Müller, pers. comm., 2010]. Finally, the HRV-Heliosat method was used to generate SSI values with a 15 min time step at the MSG HRV channel spatial resolution. Table 1 summarizes the spatio-temporal resolutions of the three considered SSI data sets.

3. Merging of ground-measured and satellite-derived surface solar radiation

RMIB is currently performing measurements of global solar irradiance (in Wm^{-2}) at 13 sites distributed over Belgium (see figure 1). Measurements are made with a 5 s time step and integrated on a 10-min basis in the RMIB data warehouse. The 10-min solar irradiation (in Whm^{-2}) data are then subject to a set of semi-automatic quality assessment tests and gaps in the time series are filled by model estimations (Journée and Bertrand 2011).

As demonstrated by Journée and Bertrand (2010), the most accurate mapping of surface solar irradiation is obtained once ground measurements and satellite-based

Table 1. Resolutions in time and space of the MSG-based SSI retrievals used in this study.

	Temporal resolution (min)	Spatial resolution
LSA SAF	30	Spectral channel resolution (~ 6 km × 3.3 km)
CM SAF	60	Spectral channel resolution remapped onto a 3 km × 3 km grid
HRV-Heliosat	15	HRV channel resolution (~ 2 km × 1.1 km)

Note: MSG, Meteosat Second Generation; LSA SAF, Land Surface Analysis Satellite Application Facility; CM SAF, Satellite Application Facility on Climate Monitoring; HRV, High-resolution visible.

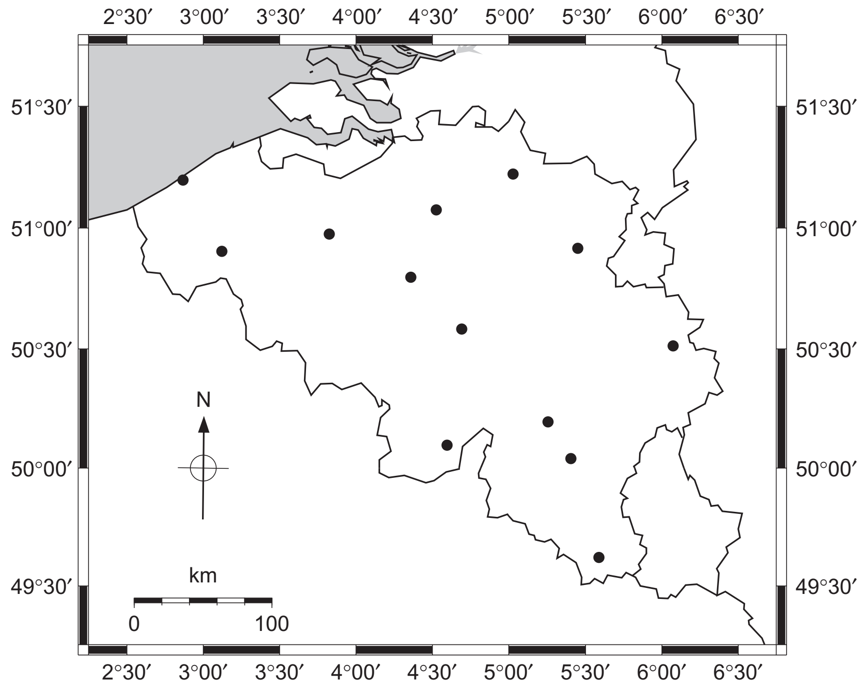

Figure 1. Site location within the Belgian territory of the ground stations used in this study.

SSI estimations are merged into a single product. The best merging method was identified to be kriging with external drift (Wackernagel 1995), which aims at interpolating a random field (e.g. the spatial distribution of surface solar irradiation) from observations at selected locations (e.g. the ground measurements) under the knowledge of a densely sampled auxiliary variable (e.g. the MSG-derived SSI values). As in Journée and Bertrand (2010), we used an exponential variogram with a range parameter fixed at 50 km to describe the spatial dependence of the random field.

4. Sensitivity to the spatio-temporal resolution of MSG-derived surface solar irradiance

In this study, we aimed to characterize the sensitivity of daily estimates of surface solar irradiation with respect to the spatio-temporal resolution of the SSI data sets derived from MSG SEVIRI data. The merging approach described in section 3 was therefore applied on daily totals of ground-measured and satellite-retrieved values. Daily values of surface solar irradiation are obtained by simple summation for the 10-min integrated ground-based measurements and by trapezoidal integration over the diurnal cycle for the instantaneous MSG-retrieved data. The quality of the daily-integrated satellite values is thus a function of the processing frequency of the SSI estimates (i.e. the number of samples available each day), in addition to the performance of the applied retrieval scheme. Another aspect is the variability of surface solar radiation within a pixel. Since the satellite retrievals are averaged values over a pixel, discrepancies with respect to pinpoint ground measurements are unavoidable. Furthermore, clouds that might block direct solar irradiance could differ from those detected from the geostationnary orbit, especially when the elevation of the Sun above the horizon is small and for high satellite viewing angles. A 10 km high cloud at 50° N is displaced by more than 10 km northwards in the satellite image. During sunrise, for instance, it blocks the Sun at a target that is further displaced more than 10 km westwards. This is called cloud parallax effect and it has an increasing impact with finer spatial resolutions.

For sensitivity analysis purposes, the resolutions in time and space of the three MSG data sets have been artificially degraded. Daily surface solar irradiation estimates derived from the MSG retrievals used at various spatio-temporal resolutions were then compared against each other by leave-one-out CV. In this way, the value at one of the measuring stations is successively omitted when mapping the daily surface solar irradiation and serves as reference to evaluate the accuracy of this map. In addition to the merged data, this study includes also estimates based solely on the satellite data as well as spatial interpolations of the ground measurements computed by ordinary kriging.

This sensitivity analysis study was conducted on the basis of two years of good quality-checked data (2008 and 2009). In total, we used a set of 488 days for which the ground data and the three MSG-derived data were available at all stations and over the entire diurnal cycle. The performance of the different mappings is assessed by the average on these 488 instances of three indices derived from the bias between the CV prediction $\hat{G}$ and the actual measurement G at the $N = 13$ locations $x_i | i = 1, \ldots, N$:

1. the CV mean bias error,

$$\mathrm{MBE}_{\mathrm{cv}} = \frac{1}{G_{\mathrm{avg}} N} \sum_{i=1}^{N} (\hat{G}(x_i) - G(x_i)), \tag{1}$$

2. the CV mean absolute error,

$$\mathrm{MAE}_{\mathrm{cv}} = \frac{1}{G_{\mathrm{avg}} N} \sum_{i=1}^{N} |\hat{G}(x_i) - G(x_i)|, \tag{2}$$

3. the CV root mean square error,

$$\mathrm{RMSE}_{\mathrm{cv}} = \frac{1}{G_{\mathrm{avg}}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\hat{G}(x_i) - G(x_i))^2}, \tag{3}$$

where $G_{\mathrm{avg}} = \frac{1}{N} \sum_{i=1}^{N} G(x_i)$ is the average solar irradiation over all stations.

4.1 *Sensitivity to temporal resolution*

To investigate the sensitivity of the daily surface solar irradiation to the temporal resolution of the MSG-based SSI estimates, the temporal resolution of the MSG data sets was degraded by considering one sample every two or four MSG slots. In this way, the 15-min resolution of the HRV-Heliosat estimations are degraded to 30 and 60 min. The LSA SAF retrieval was used with a 30-min and a 60-min temporal resolution, while a 60-min resolution was considered for the CM SAF data. The CV performance indices are provided in figure 2 for the MSG data sets, the merged data and the spatial interpolation of ground measurements. Since the MAE_{cv} and $RMSE_{cv}$ errors exhibit very similar tendencies, we will mainly focus the following results analysis on $RMSE_{cv}$.

First, the accuracy of the daily surface solar irradiation estimates degrades once the MSG data sets are used with poorer temporal resolutions. For instance, in the case of the HRV-Heliosat estimations merged with ground data, the $RMSE_{cv}$ error is increased from 9.4% to 10.2% (i.e. relative increase of 8%) and to 11.2% (i.e. relative increase of 19%) when the original 15-min resolution is reduced to 30 and 60 min, respectively. For the LSA SAF data set merged with ground data, the $RMSE_{cv}$ is larger by 0.8% (i.e. relative increase of 7%) at the 60-min resolution with respect to the original 30-min resolution. This observation has to be related to the unavoidable loss of

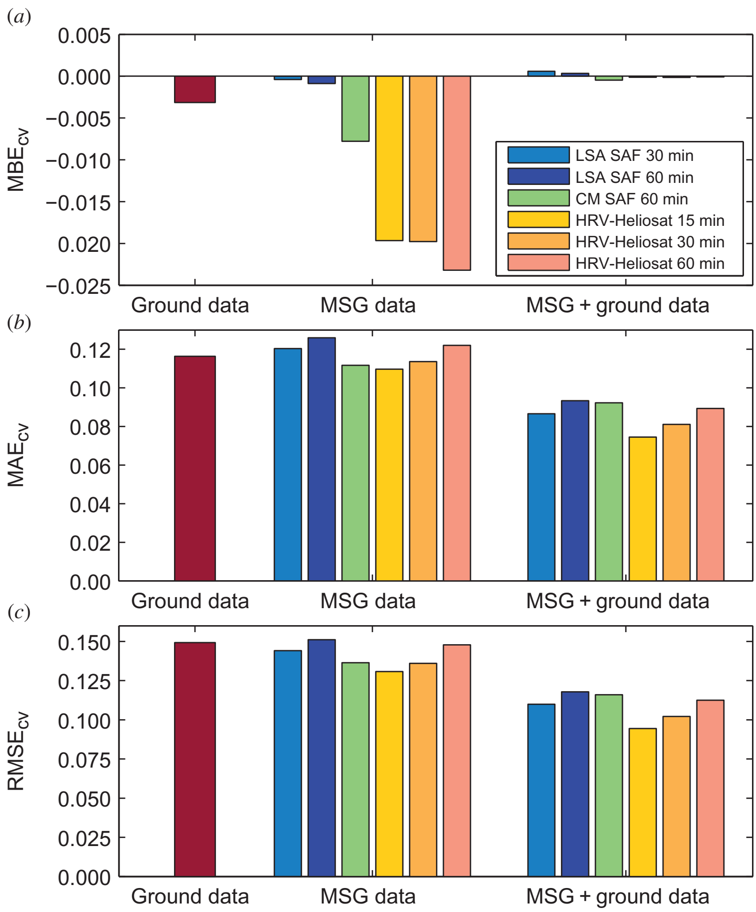

Figure 2. Cross-validation (*a*) mean bias error (MBE_{cv}), (*b*) mean absolute error (MAE_{cv}) and (*c*) root mean square error ($RMSE_{cv}$) for mappings of the daily surface solar irradiation over Belgium derived (1) by the spatial interpolation of the ground measurements; (2) from the MSG data sets used with various temporal resolutions; and (3) by merging the MSG data sets with ground measurements. All satellite data are used at their finest spatial resolutions, that is, spectral channel resolution (LSA SAF), 3 × 3 km resolution (CM SAF) or HRV channel resolution (HRV-Heliosat).

accuracy of daily integrated values when derived from time series with poorer temporal resolutions. Promising results might be expected from the CM SAF unmerged data set when used at finer temporal resolutions since it outperforms the LSA SAF and HRV-Heliosat unmerged data at the 60 min resolution. Finally, if the best performance is observed once the 15 min HRV-Heliosat data set is merged with ground data, this is partly thanks to its fine temporal resolution, but not only, since the 30 min HRV-Heliosat merged data is still 7% better in terms of $RMSE_{cv}$ than the 30 min LSA SAF merged data (i.e. $RMSE_{cv}$ of 10.2% vs. 11%).

What is also very remarkable in figure 2 is the benefit associated to the merging of ground-based and MSG-derived SSI values, as previously noticed by Journée and Bertrand (2010). The reduction of the $RMSE_{cv}$ error ranges from 2% (60-min CM SAF) to 3.6% (15-min HRV-Heliosat) (i.e. a relative improvement of 15–28%). The merging approach furthermore enables to reduce the MBE_{cv} error very close to 0.

4.2 *Sensitivity to spatial resolution*

Although the MSG data were used at various spatial resolutions to estimate SSI (i.e. resolution of either the HRV or the spectral channels), the sensitivity of the MSG-derived data sets to spatial resolution can hardly be evaluated from figure 2 as different retrieval algorithms are used for each resolution. Instead, the same algorithm should be used to retrieve SSI at various MSG footprints resolution (i.e. 1×1 (spectral pixels), 3×3 (spectral pixels), 1×1 (HRV pixels), 3×3 (HRV pixels)).

In this study, we evaluated the sensitivity to the spatial smoothing of SSI values by computing averages on pixel aggregates of various sizes. In this way, the degradation in spatial resolution occurs after, instead of before, application of the SSI retrieval algorithm. Comparisons were performed for spatial resolutions ranging from one MSG spectral pixel to blocks of 3×3 pixels for the LSA SAF data set, from 3 km $\times$ 3 km to 15 km $\times$ 15 km areas for the CM SAF data set, and from one HRV pixel to blocks of 9×9 HRV pixels for the HRV-Heliosat data set (see figure 3).

For the three considered MSG-derived data sets, slight improvements are obtained with coarser resolutions, that is, the $RMSE_{cv}$ error is on average reduced from 11% to 10.5% (LSA SAF), from 11.6% to 10.9% (CM SAF) and from 9.4% to 9.1% (HRV-Heliosat) between the finest and the coarsest spatial resolutions for the MSG data sets merged with ground measurements. While this finding holds for daily SSI, spatial resolution might be more important for the calculation of instantaneous SSI.

5. Conclusions

Our study estimated the sensitivity of the daily surface solar irradiation over Belgium retrieved from MSG data with respect to the underlying spatio-temporal resolution. For that purpose, the resolution in time of the considered MSG-derived data sets was artificially degraded by taking one sample every two or four MSG slots. Regarding the sensitivity to spatial resolution, the values derived from the HRV and spectral channels could not be properly compared because different SSI retrieval methods are used for both channel types. To overcome this difficulty, the MSG-derived SSI data were averaged on pixel aggregates of various sizes. In this way, the outcomes of a same retrieval method could be compared with respect to the resolution of the posterior spatial smoothing. In a future study, we will evaluate the impact of a degradation in spatial resolution at the level of the MSG images, that is, before application of the SSI

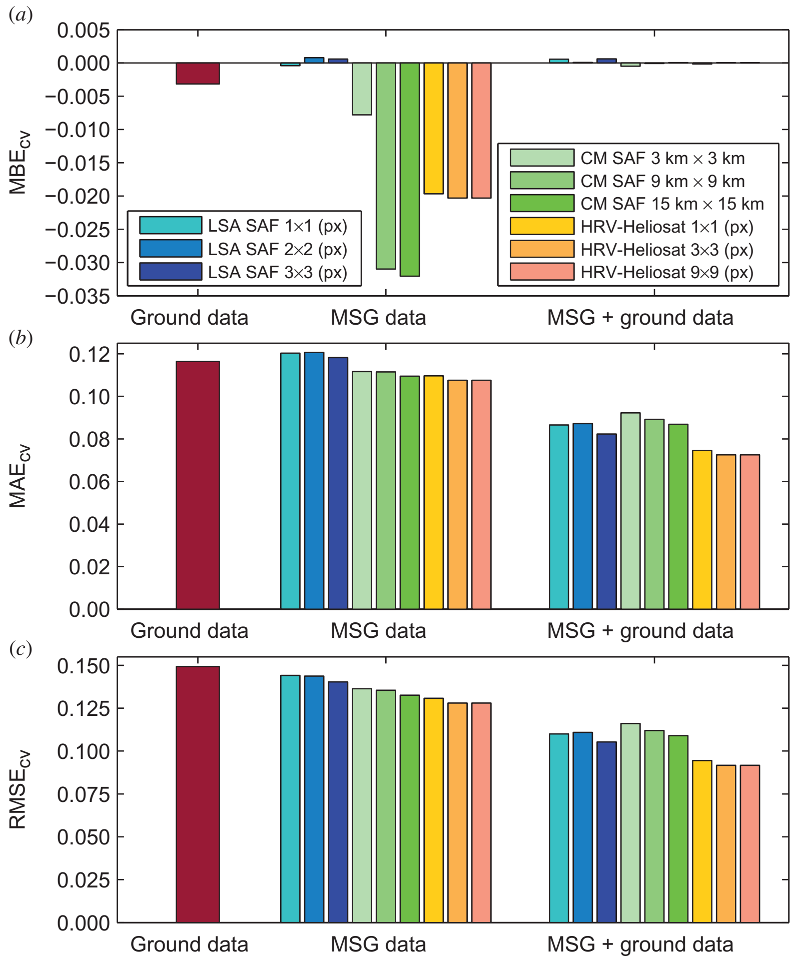

Figure 3. Cross-validation (*a*) mean bias error (*MBE$_{cv}$*), (*b*) mean absolute error (*MAE$_{cv}$*) and (*c*) root mean square error (*RMSE$_{cv}$*) for mappings of the daily surface solar irradiation over Belgium derived (1) by the spatial interpolation of the ground measurements; (2) from the MSG data sets used with various spatial resolutions; and (3) by merging the MSG data sets with ground measurements. All satellite data are used at their finest temporal resolutions, that is, 30 min (LSA SAF), 60 min (CM SAF) or 15 min (HRV-Heliosat). The abbreviation 'px' is used for 'pixel'.

retrieval algorithms. Following Journée and Bertrand (2010), the daily MSG-retrieved values were merged with ground-based measurements.

For the considered MSG-based SSI data sets, we observed a much higher sensitivity to temporal resolution than to spatial resolution. For instance, in the case of the HRV-Heliosat data merged with ground data, the RMSE$_{cv}$ varied from 9.4% to 11.2% (i.e. a relative increase of 19%) when the temporal resolution was degraded by a factor of 4 (i.e. from 15 to 60 min), but only by 0.3% (i.e. a relative variation of 3%) when the spatial resolution was degraded by a factor of 81 (i.e. from 1 pixel to blocks of 9 × 9 pixels). Regarding sensitivity to temporal resolution, the best performance was obtained with the finest resolutions, which allow a more accurate estimation of daily integrals of MSG-based SSI retrievals. On the other hand, a slight degradation in performance was observed when using finer spatial resolutions. While this result might seem counter-intuitive, it can be partly explained by the limitations of current SSI retrieval algorithms: cloud parallax, cloud shadows and navigation errors can potentially lead to spatial displacements of satellite-retrieved SSI in the order of several MSG HRV pixels. It is also important to note that part of the $RMSE_{cv}$ does not result from the retrieval method, but from the mismatch between spatially averaged satellite observations and pinpoint ground measurements (Zelenka *et al*. 1999).

This study was conducted for a mid-latitude region with a rather flat orography. Different results might be obtained for other areas. In particular, we expect the sensitivity to spatial resolution to be more significant in regions with strong influence of meso-scale meteorology, such as at coastlines and in highlands. As an example, Dürr and Zelenka (2009) highlighted the benefits of using finer spatial resolutions to estimate SSI over the Alpine region.

Nevertheless, the outcomes of this sensitivity analysis are very encouraging as the future Meteosat Third Generation satellites (Bézy *et al*. 2005) will feature an improved temporal resolution (10 min) while the spatial resolution will lie in between the resolutions of the MSG HRV and spectral channels (i.e. 1–2 km at subsatellite point).

Finally, this study and Journée and Bertrand (2010) further demonstrated that the merged solar radiation data set is superior to either of the satellite-derived and ground-based datasets alone. The best performance was observed for the HRV-Heliosat data set merged with ground observations.

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