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Availability and variability of solar radiation data for the modelling of solar thermal installations in Andalusia (Spain)

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Abstract

A comprehensive analysis was carried out on the data from various weather station networks in Andalusia (Southern Spain) and standard climate data sources. Special attention was given to characterizing the different sources of uncertainty that need to be taken into account when inputting solar radiation data used for solar thermal system modelling - in terms of geographical and statistical representativeness and in terms of the estimation/measuring procedure considered in direct and diffuse fraction decomposition, a key factor in concentrating solar system simulation.

Keywords: solar radiation database; direct radiation; diffuse radiation.

1. Introduction

Prior to any simulation of a solar thermal system, one needs to know the typical climatic conditions of the proposed installation site. Existing standard climate databases generally provide good spatial and temporal information together with some extra calculation capabilities. However, given the global nature of most of these databases, they react very slowly to the increasing amount of local climate information sources that, at present, can provide more specific data related to variability and actual meteorological patterns. These sources, in turn, can increase the confidence of the standard data both by direct comparison and by establishing the corresponding uncertainty intervals.

Within the framework of a regional project aimed at assessing the potential use of solar energy as process heat in Andalusia (Southern Spain), several system simulation codes have been used. Although, as a first step, an overall analysis can be carried out based on standard meteo inputs (Dumortier, et al., 2009; Perez, et al., 2001; Súri, 2007; Wald, 2006), the existence of a relevant number of complementary data sources allows one to better characterize the eventual uncertainties to be considered when inputting solar radiation data into modelling tasks.

2. Weather stations networks in Andalusia

Andalusia has an extensive network of both automated and manual weather stations distributed evenly throughout the region (Fig. 1), managed by regional institutions (CMA, 2012) and by the State Spanish Meteorology Agency (AEMET, 2012).

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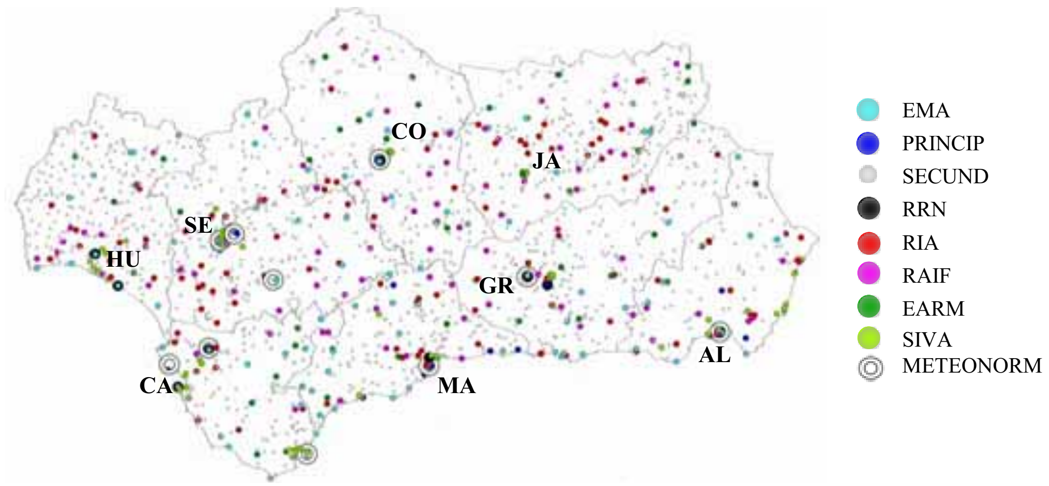


Fig. 1. Spatial distribution of the main weather station networks in Andalusia (Southern Spain).

The number of Andalusian weather stations and the main climatic variables measured are shown in Table 1. In Andalusia, there are about 300 weather stations which measure solar radiation; however very few weather stations measure direct and diffuse radiation.

Due to the scant availability of measured data for direct irradiation, where necessary it has been estimated on a horizontal surface, H_b, by the expression:

$$H_b = H - H_d \quad \text{(eq. 1)}$$

Tab. 1. Availability of the principal climatic variables for the main weather station networks in Andalusia and the minimum time-scale availability (Global solar irradiation, *H*; direct normal irradiation, *DNI*; diffuse irradiation, H_d; temperature, *T*, and wind velocity, *u*).

Institution	Name of weather station network	Short name	*H*	*DNI*	H_d	*T*	*u*	Minimum time scale
			[number of weather stations]					
AEMET	Automatic weather station	EMA				108	105	10'/ Hour
	Main weather station	PRINCIP	3		1	14	19	10'
	Secondary weather station	SECUND	1		1	73	55	Day
	Radiometric national network	RRN	9	4	7	8	8	Hour
Junta de Andalucía	Agroclimatic information	RIA	108			108	108	Hour
	Alert and phytosanitary information	RAIF	90			90	90	Hour
	Automatic and remote weather station	EARM	45			45	45	Hour
	Information system for environmental monitoring	SIVA	51			60	64	Hour
Total			**307**	**4**	**9**	**506**	**494**	

3. Comparison of solar radiation sources

The source of the measured data was the National Radiometric Network, RRN, (AEMET, 2012), providing data for global solar irradiation, *H*, beam solar irradiation, *DNI*, and diffuse solar irradiation, H_d (Tab. 1). The weather stations from which the measured solar radiation data came are located in 7 provincial capitals; Almería (AL), Cádiz (CA), Córdoba (CO), Granada (GR), Huelva (HU) and Málaga (MA). Tab. 2 shows the daily coverage data over a 10-year period (01/01/2001 to 31/12/2010) from the main RRN weather stations.

Using the 10 years of measured values from the RRN stations in Andalusia (Tab. 1) for global, direct and diffuse solar irradiation, various sources of solar radiation have been analysed (Tab. 3), with radiation data from the Andalusia EA, METEONORM, HELIOCLIM-3, and SATEL-LIGHT. Special attention was paid to assessing the geographical and statistical representativeness of standard data as well as the estimation procedure considered for direct and diffuse decomposition on an hourly, daily and monthly time scale.

Tab. 2. Daily coverage of the measured climatic variables from the main radiometric national network (RRN) weather stations in Andalusia for the period between 01/01/2001 and 31/12/2010 (Global solar irradiation, *H*; direct irradiation, H_b; diffuse irradiation, H_d; temperature, *T*, and wind velocity, *u*).

Parameter	weather station location (RRN) [*Latitude* and *Longitude*]					
	AL [36.8º, -2.4º]	CA [36.5º, -6.3º]	CO [37.8º, -4.8º]	GR [37.1º, -3.6º]	HU [37.3º, -6.9º]	MA [36.7º, -4.5º]
H	98%	44%	46%	83%	40%	59%
H_b, H_d	95%	31%	14%	81%	37%	46%

Starting from the cumulative frequency curves for different irradiation ranges (Fig. 3), we performed a values comparison using the Kolmogorov-Smirnov test, measuring the maximum distance, D_{KS}, between the cumulative frequency curves of the modeled values, CDF_{mod}, and the measured values CDF_{mea}. The Kolmogorov–Smirnov test Integral (KSI) is the integral of the area between the CDFs for the modelled and measured values (Espinar, et al., 2009; Massey, 1951).

$$D_i = CDF_{mod}(i) - CDF_{mea}(i) \quad \text{(eq. 2)}$$

$$D_{KS} = max|D_i| \quad \text{(eq. 3)}$$

$$KSI = \int_{x_{min}}^{x_{max}} |D_i| \, dx \quad \text{(eq. 4)}$$

A KSI percentage [KSI %] is obtained by normalizing by the critical area, $a_{critical}$:

$$KSI\% = \frac{KSI}{a_{critical}} 100 \quad \text{(eq. 5)}$$

where $a_{critical}$ is calculated for a number of available data (n≥35) and for a 99% level of confidence:

$$a_{critical} = \frac{1.63}{\sqrt{n}} (x_{max} - x_{min}) \quad \text{(eq. 6)}$$

The RMSE [MJ m^{-2}] between the modelled, Y_{mod}, and measured, Y_{mea}, values is obtained for each variable and weather station over the daily and monthly periods. The NRMSE [%] is obtained by normalizing by the average of the measured values.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(Y_{mod}(i) - Y_{mea}(i)\right)^2}{n}} \; ; NRMSE = \frac{RMSE}{\overline{Y_{mea}}} 100 \quad \text{(eq. 7)}$$

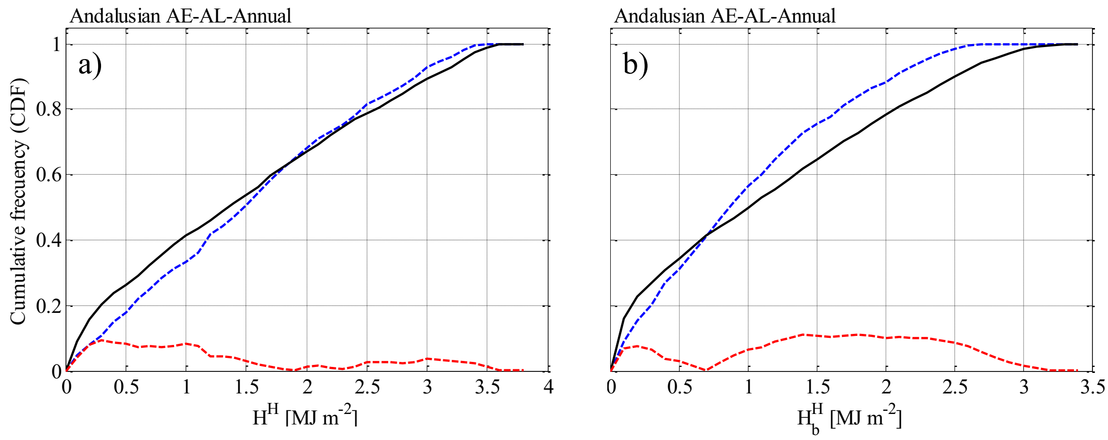
Tab. 3. Radiation sources compared to the values measured at weather stations. [adapted from (Suri, et al., 2008)]

Product	Provider	Source of data	Area	time period	time scale	variables	RMSE/MBE [%] for G^H
Radiation data exploitation of Andalusia (AAE, 2014)	Andalusian Energy Agency (AEA)	Ground (RIA/RAIF)	Andalusia (Spain)	measured data, interpolations and typical meteorological years	hourly	G, G_b, G_d, T, u	-
METEONORM v7.0 (METEOTEST, 2014)	METEOTEST	Ground	worldwide	measured monthly data from ground stations, interpolation and estimation typical meteorological years	monthly hourly	G, G_b, G_d, T, u	6.2/0 (Remund, 2008)
HELIOCLIM-3 (SODA, 2014)	MINES ParisTech - Armines (France)	Satellite	from -66° to 66° (lat. and long.)	2004 - onward	15 minutes	G, G_b, G_d	25/3 (Beyer, et al., 2009)

SATEL-LIGHT (SATEL-LIGHT, 2014)	European project - ENTPE	Satellite	Europe	1996 - 2000	30 minutes	*G, G_b, G_d*	27/-2 (Beyer, Polo Martinez, Suri, Torres, Lorenz, Müller, Hoyer-Klick and Ineichen, 2009)

3.1. Hourly values

Figure 3 shows the annual errors for different hourly ranges of global, direct and diffuse solar irradiation, between measured and modelled values from the Andalusian EA database located in Almería. There is more error (the dotted red line) at low irradiance, where the observed values are greater than the estimated values.



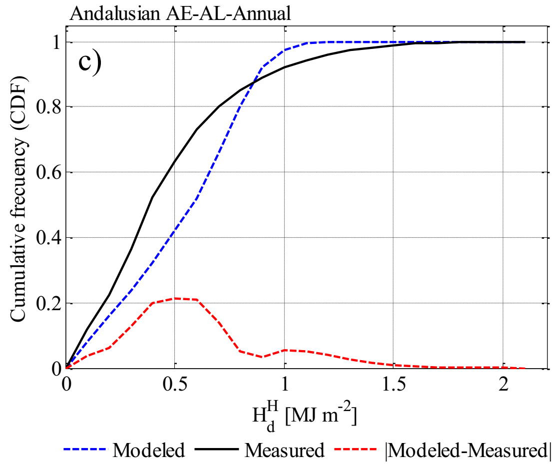


Fig. 2. Annual cumulative frequency for modelled and measured hourly values of a) global, H^{H}, b) direct , H_b^H, and c) diffuse, H_d^H, solar irradiation from the Andalusian EA data source in Almería (AL).

The monthly and annual errors for hourly global irradiation, *KSI%*, show variability between different locations (for all databases) of between 25-30% (Fig. 4b). *KSI%* is higher in winter for the database of the Andalusian EA, and Satel-light; whereas it is higher in spring-summer for Helioclim-3. For horizontal direct solar irradiation (Fig. 4b), the error is greater in the autumn-winter for Andalusian EA and Satel-light; in summer, it is higher for Meteonorm. In the case of diffuse solar irradiance (Fig. 4c), the error is greater in winter for Andalusian EA, and in summer for Meteonorm and Helioclim-3. The highest database error is for Andalusian EA. This may be because the Andalusian EA database uses climate data from the RIA network, which measures radiation with pyranometers that have less accuracy and wavelength range than the RRN pyranometers.

3.2. Daily values

For daily irradiation values, the NRMSE error is higher in spring and autumn for all databases measuring global (Fig. 2a), direct (Fig. 2b), and diffuse (Fig. 2c) solar irradiation. The highest monthly database errors came for Meteonorm and Helioclim-3. The highest daily error, coming from the Meteonorm database, may be due to the random value generation process of global, direct and diffuse solar radiation that this software uses.

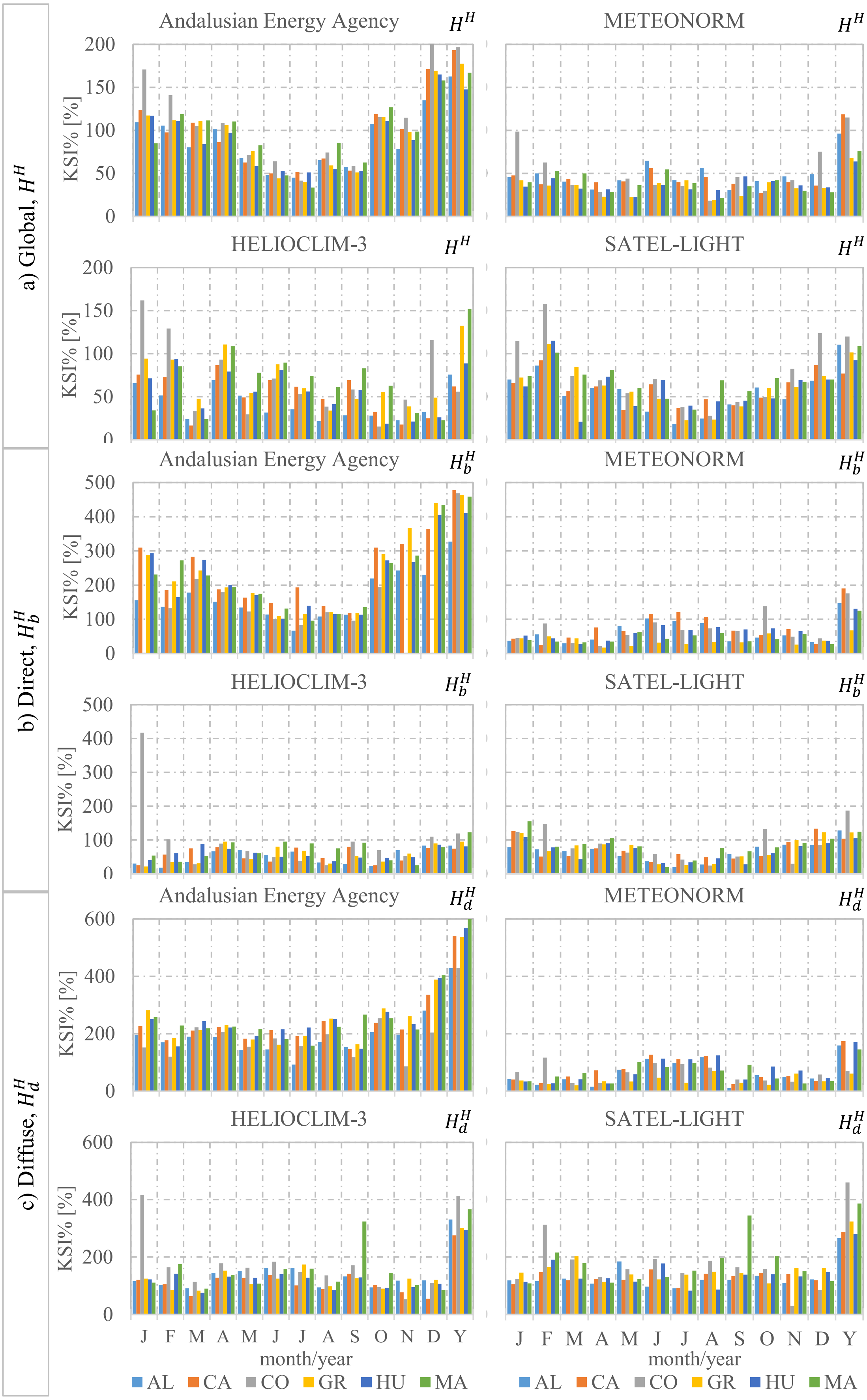


Fig. 3. Monthly and annual error of use for the hourly a) global, H^H, b) direct, H_b^H, and c) diffuse, H_d^H, solar irradiation from the Andalusian EA, Meteonorm, Helioclim-3 and Satel-light sources for the main radiometric national network (RRN) weather stations in Andalusia.

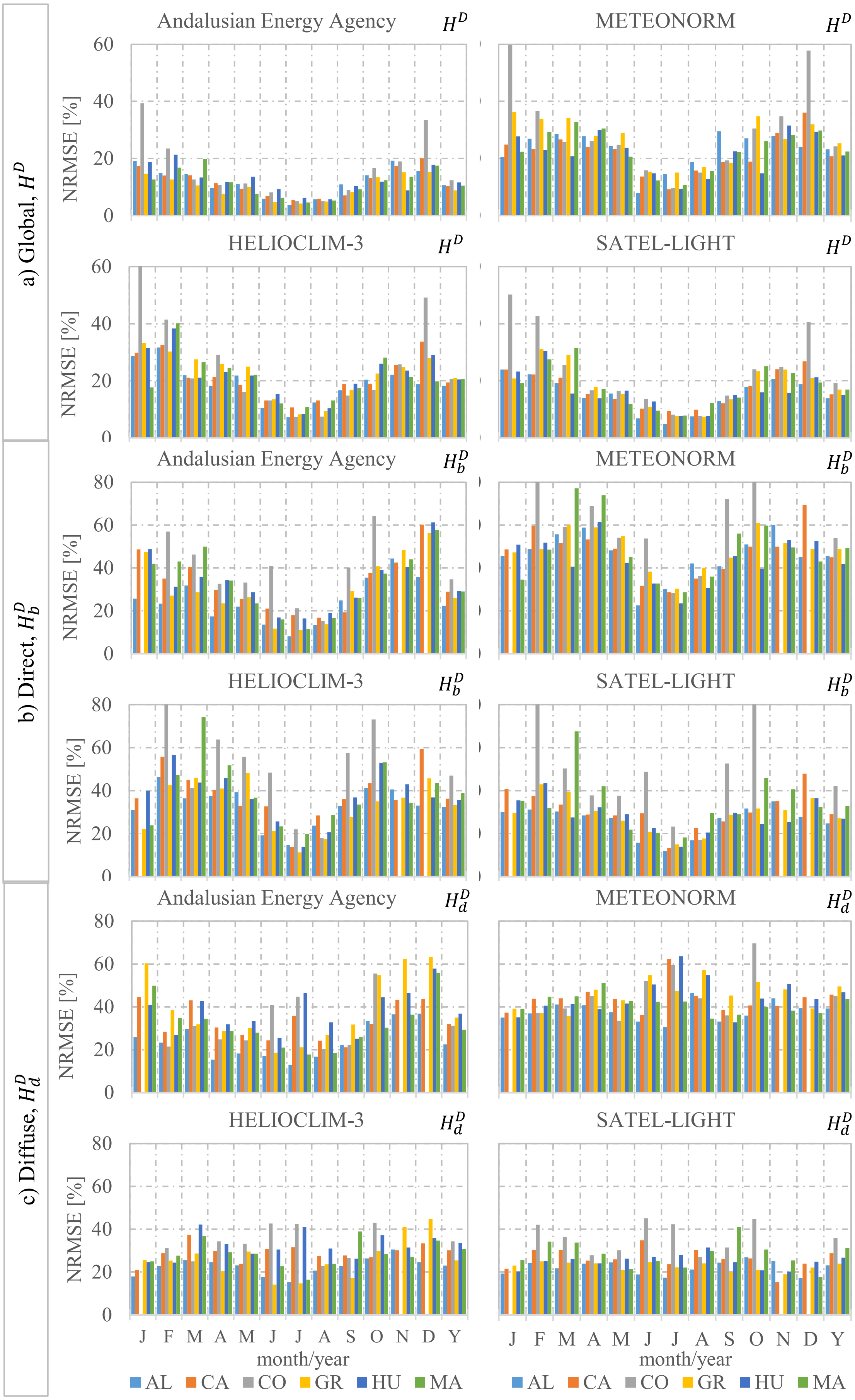


Fig. 4. Monthly and annual error of use for the daily a) global, H^D, b) direct, H_b^D, and c) diffuse, H_d^D, solar irradiation from the Andalusian EA, Meteonorm, Helioclim-3 and Satel-light sources for the main radiometric national network (RRN) weather stations in Andalusia.

3.3. Monthly values

The average monthly NRMSE error is 7±4%, 14±2% and 16±4% for global, direct and diffuse solar irradiation, respectively (Fig. 5).

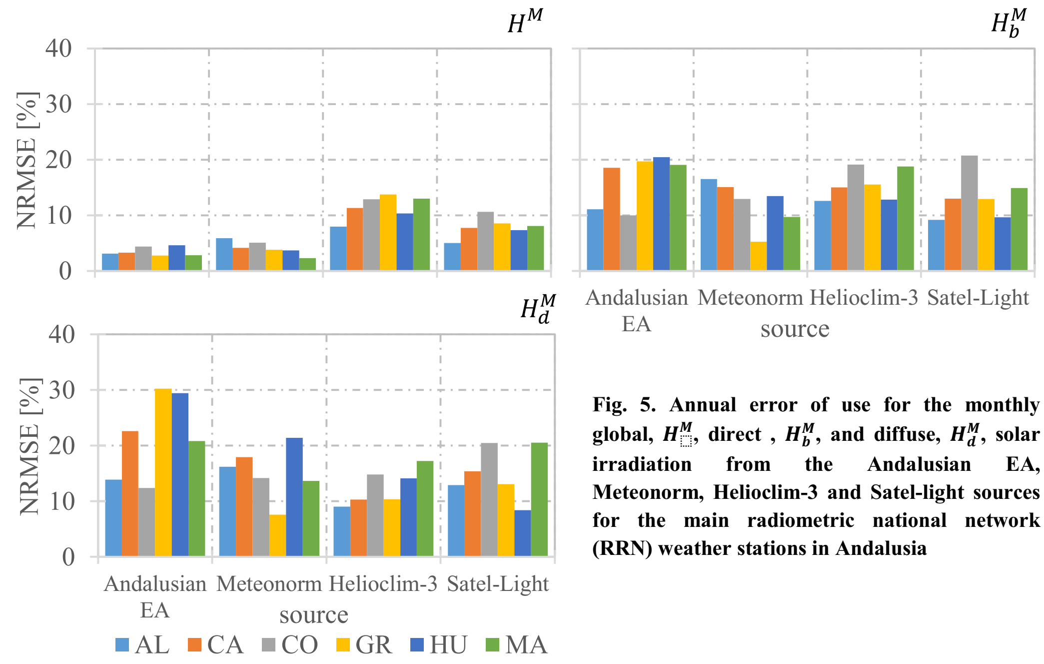


Fig. 5. Annual error of use for the monthly global, H^M, direct, H_b^M, and diffuse, H_d^M, solar irradiation from the Andalusian EA, Meteonorm, Helioclim-3 and Satel-light sources for the main radiometric national network (RRN) weather stations in Andalusia

Tab. 4. Annual KSI%, RMSE and NRMSE error of use for the hourly, daily and monthly global, H, direct, H_b, and diffuse, H_d, solar irradiation for different sources in the main radiometric national network (RRN) weather stations in Andalusia.

		Hourly			Daily			Monthly		
Source		H^H	H_b^H	H_d^H	H^D	H_b^D	H_d^D	H^M	H_b^M	H_d^M
Andalusian EA	KSI% [%]	174±19	435±58	518±73	27±5	140±39	191±69	5±1	29±7	48±21
Meteonorm	KSI% [%]	90±24	140±43	130±51	25±9	75±21	78±13	7±2	21±9	24±8
Helioclim-3	KSI% [%]	94±39	96±21	330±51	77±17	77±21	77±46	19±4	17±3	33±16
Satel-Ligth	KSI% [%]	102±15	128±30	334±75	49±9	51±10	140±87	12±2	15±2	43±25
LSD	KSI% [%]	*31*	*49*	*77*	*13*	*30*	*73*	*3*	*7*	*NS*
Andalusian EA	RMSE [MJ m^{-2}] / (NRMSE [%])				1.9±0.2 (11±1)	3.8±0.7 (28±4)	1.8±0.3 (31±5)	19.1±4.3 (4±1)	66.6±19.0 (16±5)	37.1±10.0 (22±8)
Meteonorm	RMSE [MJ m^{-2}] / (NRMSE [%])				4.1±0.3 (23±2)	6.4±0.7 (47±4)	2.6±0.3 (45±3)	22.8±6.7 (4±1)	49.3±16.9 (12±4)	26.7±7.6 (15±5)
Helioclim-3	RMSE [MJ m^{-2}] / (NRMSE [%])				3.6±0.2 (20±1)	5.0±0.9 (37±5)	1.7±0.4 (30±4)	62.9±10.8 (12±2)	63.2±11.1 (16±3)	22.6±7.3 (13±3)
Satel-Ligth	RMSE [MJ m^{-2}] / (NRMSE [%])				2.9±0.2 (16±2)	4.1±1.0 (30±6)	1.7±0.5 (28±5)	43.0±8.9 (8±2)	54.2±17.4 (13±4)	27.3±11.1 (15±5)
LSD	RMSE [MJ m^{-2}] / (NRMSE [%])				*0.3 (2)*	*1 (6)*	*0.4 (5)*	*9.7 (2)*	*NS NS*	*NS (6)*

LSD: Least significant difference; NS: No significant difference (p<0.05).

There are significant differences in the annual error from the various databases when generating solar radiation data (Tab. 4).

For annual beam solar irradiation values, when comparing data generated by METEONORM for measured data in Seville between 2000-2012 (Silva-Pérez, et al., 2014), they obtained an RMSE error = 232 MJ m^{-2} (11%), similar to the one obtained in this study.

By performing a daily global irradiation estimation, with measured values from nearby weather stations, (Vázquez, et al., 2014) obtained an annual error lower than 5% with the RRN data for northern Spain.

4. Conclusions

There are significant variations in accuracy between databases. No definitive database exists; instead, one must choose between one or other of the databases taking the following into account: the location, the purpose of the application, the time scale and the date of availability etc... all of which are required for the estimated data.

The radiation error estimation for different databases reduces with increasing time scale.

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