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## CAMS Solar radiation products Regular Validation Report, Issue #34, March-May 2021

Mireille Lefèvre

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# **D1.3.1**

## **Regular Validation Report**

### **Issue #34**

#### **M-A-M 2021**

## **CAMS2-73**

### **Solar radiation products**

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## Executive summary

The CAMS Radiation Service (CRS) is continuously monitored against ground-based irradiance observations. This includes stations in various geographical locations and climates (see maps in [Fig. 2.1](#) and description in [section 4.2](#)). Several stations being affected by large satellite viewing angles are included by intention to provide quantitative insight where the CRS may become unreliable for some applications ([Tab. 2.1](#)). From the #31 issue onwards, a new table of the ground datasets performance is presented with the amount of data rejected / retained for each station by the quality check ([Tab. 2.2](#)).

From #30 issue onwards, the protocol of validation (see [Annex A.5](#)) has been changed regarding the threshold applied for the usable measurements. For the consistency, the same new protocol has been applied to every quarter in the multi-annual plots. From #33 issue onwards, the validation of McClear (the cloud-free module of the CRS) is performed along with the CAMS-RAD module for cloudy skies. McClear can be computed for all sites at the global scale, thus stations outside the Meteosat field of view can be added. For this issue five BSRN stations (Tateno in Japan, Granite Island and Langley in United States, Syowa in Antarctica and Ny-Ålesund in Spitzbergen) are selected. More stations will be further added in order to increase the number of available datasets for the validation of McClear. Indeed, the procedure for selecting cloud-free instants in the period (see [Annex A.8](#)) requires stations to have at least 2 products  $G$ ,  $D$  and/or  $B$  and an integration time of 1 min. These constraints eliminate many stations used for the CAMS-RAD validation. Moreover, for a station eligible, the filter on cloud-free instants may eliminate many values especially in winter time. Stations with a too small number of samples for the computation of statistical indicators have been eliminated. The [table 2.1](#) lists the stations retained for the period March to May (MAM) 2021 with information on the availability of a validation for the modules McClear or CAMS-RAD.

For MAM 2021, the correlation is very good for global irradiances ( $G$ , [Fig. 3.4](#)) except for Sonnblick located at a mountain top, and excellent for the cloud-free irradiances  $G_c$  for all stations. The correlation is good for diffuse irradiances ( $D$ , [Fig. 3.5](#)) and beam ( $B$ , [Fig. 3.6](#)) except for Sonnblick and Izaña both located on mountain tops. Cloud-free skies correlations  $B_c$  and  $D_c$  are generally lower than those for  $B$  and  $D$ .

Regarding the clearness indices, the all-skies beam  $KT_B$  are at the same level as for  $B$  for all stations. Apart from this case and whatever the period, the clearness indices correlations are lower than those for the irradiances, and lower for the cloud-free skies compared to all-skies.

### Global irradiance

The bias for the global irradiance is null or low for 13 stations and noticeable or large for 18 stations out of 31 ([Tab. 3.1](#)). It is a better performance than in the previous period MAM 2020 (with respectively 11 and 18 stations out of 29), considering that the worse performances in 2021



occurred at stations not present in 2020, i.e., Izaña (-9.4 %), Sonnblick (-19.7 %) and Reunion Island (-8.4 %), 2 of them being at a high elevation. The highest biases are negative ([Fig. 3.1](#)) as observed in DJF 2021 (issue #33). During MAM 2020 (issue #30 with CRS v3.2) a clear trend from highest positive biases to lowest negative biases from North to South were observed. The trend is not observed anymore since DJF 2021 and this can be attributed to the upgrade to CRS v4.0. This improvement is also well observed on the frequency distributions. With the previous CRS v3.2 stations with frequent cloudy skies (low  $KT_G$ ) overestimated  $G$  (positive bias), while stations with frequent clear skies (high  $KT_G$ ) underestimated  $G$  (negative bias). With the CRS v4.0 such a trend is not visible anymore: the distribution of  $G$  is more homogeneous between stations and the discrepancy with ground measurement distributions is reduced ([Fig.3.7](#)). As a whole, the frequency distributions of all-skies  $G$  and cloud-free  $G_c$  are good, but those for  $KT_G$  present some discrepancies. The distribution of clearness index  $KT_G$  in a large range [0.1, 0.7] is slightly over-represented at the expense of lowest  $KT_G < 0.1$  and mainly highest  $KT_G > 0.7$  ([Fig. 3.8](#)) leading to an underestimation for most stations. Regarding McClear this distribution is good except as expected for stations Izaña and Sonnblick at high elevations, and Ny-Ålesund at a high latitude. The multi-annual biases ([Fig. 3.16b](#)) highlight a better overall performance for the 2017-2020 MAM quarters than in previous issue #30 with CRS v3.2. No large discrepancy is observed for the MAM quarters over 5 years, except for enerMENA stations which exhibit recurrent problem of maintenance (see [section 4.4](#)).

It should be noted that mountain top stations (Sonnblick and Izaña) observe a better McClear performance (1.7 % and -0.9 % respectively) with the IFS cycle CY47r1 although all-skies performance remains bad (-20 % and -9 % respectively). McClear has good overall performance except at extreme latitudes (Syowa in Antarctica and Ny-Ålesund in Spitzbergen) whatever the year, and at enerMENA stations.

The monthly means of the estimated  $G$  ([Fig. 3.13](#)) are identical or close to those of the measurements at all stations. The monthly standard deviations that highlight the dynamics of the dataset are also close to those of measurements for both McClear and CAMS-RAD.

### Diffuse irradiance

The bias for the diffuse irradiance ([Fig. 3.2](#)) is null or low for 11 stations out of 18, and noticeable or large for 7 stations. This is a similar result as previous period MAM 2020 (CRS v3.2) with respectively 9 and 6 out of 15. The all-skies multi-annual biases for CRS v4.0 ([Fig. 3.17b](#)) show an overall slight shift towards lower or negative values compared to CRS v3.2 ([Fig 3.17b](#) in issue #30), thus an improvement of the cloud detection in the new CRS. Highest biases are negative. Only Sonnblick at a high elevation presents a very large and negative bias.

The trend from negative bias for stations with frequent cloudy skies, to positive bias for stations with frequent clear skies, observed with CRSv3.2 is not observed anymore. Actually, the frequency distributions of  $D$  ([fig. 3.9](#)) shows a good adequation between measurements and model outputs. The monthly means of the estimated  $D$  ([Fig. 3.14](#)) display some slight discrepancies with a slightly weaker dynamic compared to measurements. The distribution of  $KT_D$  ([Fig. 3.10](#)) follows a different



pattern than  $D$ : medium  $KT_D$  are always over-represented, at the expense of higher  $KT_D$  and lower  $KT_D$ . That illustrates a lack of dynamic for the  $KT_D$ , contrary to  $D$ .

Regarding McClear ([Fig. 3.2](#), [Fig. 3.14](#)) all biases are positive (overestimation with a higher dynamic compared to measurements), except top mountain stations Izaña and Sonnblick (underestimation with a lower dynamic compared to measurements), and high latitude stations Syowa and Ny-Ålesund (underestimation with a good representativity of the dynamic). Apart these “extreme” areas, McClear overestimates the diffuse component. It should be noted that the larger biases concern enerMENA stations. The frequency distribution ([Fig. 3.10](#)) of  $KT_{Dc}$  is bad for enerMENA stations, while the distribution is correct for most of the BSRN stations. It is thus difficult to attribute the bias to McClear or to enerMENA stations. More stations, and validation of other seasons are needed to conclude on this point.

Contrary to  $D$ , results are not satisfactory for  $D_c$  whatever the year ([Fig. 3.17b](#)). As the diffuse component is a minor contribution to the global clear-skies irradiance  $G_c$ , that does not highly impact  $G_c$ .

### Direct normal irradiance

The trends observed for  $B$  and  $B_c$  are opposite to those observed for  $D$  and  $D_c$ . The bias for  $B$  ([Fig. 3.3](#)) is mostly positive (vs negative for  $D$ ), also illustrated with the frequency distributions ([Fig. 3.11](#)). An over-representation of medium range [100-900]  $W m^{-2}$  is obtained at the expense of lower values or higher values with an overall overestimation and loss of dynamic. The  $B$  multi-annual biases ([Fig. 3.18b](#)) for CRS v4.0 compared to CRS v3.2 ([Fig. 3.18b](#) in issue #30) show an overall shift towards positive values leading to reduced absolute values.

Contrary to all-skies, clear-skies  $B_c$  are underestimated (vs overestimated for  $D_c$ ) except for top mountain stations of Sonnblick and Izaña. No great discrepancy over the five years for McClear can be observed for the MAM quarter. The monthly means of the estimated  $B$  and  $B_c$  ([Fig. 3.15](#)) present slight discrepancies at most stations, with a dynamic close to that of measurements for both CAMS-RAD and McClear.

Overall, CAMS-RAD exhibits for this MAM quarter better performance with the CRS v4.0 (2021) compared to CRS v3.2 for the 3 components. Results are satisfactory except for stations at high elevations, i.e., Sonnblick (3109 m), Izaña (2373 m), and for stations at high latitudes, i.e., Syowa (69° S) and Ny-Ålesund (78.9° N). Besides these “extreme” area, bad results persist at the enerMENA stations which exhibit recurrent problems of maintenance but also offer insight into aerosol-affected regions with sparse coverage from other networks. Another main result concerns the bias trends from North to South, or from stations with frequent cloudy skies to stations with frequent cloud-free skies. These trends were not observed in DJF 2021 and MAM 2021 confirms this result, due to an improvement of the cloud detection in the new CRS v4.0. This is in accordance with a better representation of the frequency distributions with CRS v4.0 for  $G$  and  $B$  irradiances for all-skies and for cloud-free skies, although this is not the case for  $D$  and  $D_c$ .



Regarding McClear, performance for  $B_c$  are much better than for diffuse  $D_c$ . The opposite trends in diffuse and direct components combine each other to finally exhibit good results for the global irradiance.

## 1 Introduction

The CAMS Radiation Service, abbreviated as CRS, delivers estimates of the solar radiation arriving at ground level on a horizontal surface. Outcomes of the CRS have to be validated on a periodic basis. Following practices in CAMS, this validation is performed every quarter. Following current practices, the CRS irradiances are tested against qualified ground measurements measured at several ground-based stations serving as reference. These ground measurements are coincident in time with the CRS estimates.

On 28 June 2021, version 4.0 of the CRS was introduced with a new version APOLLO Next Generation (APOLLO\_NG) provided by the DLR that improves cloud detection and cloud physical parameters; includes an improved handling of circumsolar irradiances; and includes the most recent CAMS IFS cycle update for cloud-free parameters aerosols, water vapour and ozone. For consistency, this new version 4.0 is used from now on back to 2016 for the multi-annual assessments.

This report is issue #34 of a regular report performed with version 4.0 of the CRS. It deals with hourly means of global, diffuse, and direct irradiances for the period March to May 2021, abbreviated as MAM 2021.

In #24 of this report a multi-annual assessment was introduced for each station as a 3-years timeseries in Annex C. This assessment is provided once a year for the yyyyQ3 report (DJF datasets) when in-situ measurements are completed for the year. This has made the quarterly validation reports very large. Therefore, from issue #25 onwards detailed results are partly provided in a zip archive supplement as individual files in a well-organized folder structure.

From #27 (2019Q3 report) onwards, multi-annual statistical indicators of the respective season are given in section 3.

From #31 (2021Q1 report) onwards, a summary of the quality check operated on each station is given in section 2.

From #33 (2021Q3 report), the validation is performed on both cloud-free and all-sky components of the CRS, namely McClear and CAMS-RAD modules (see <https://atmosphere.copernicus.eu/solar-radiation> and the User Guide published there). Contrary



to CAMS-RAD which is available at sites inside the Meteosat field of view only, McClear radiation can be computed at the global scale.

Figure 1.1 summarizes the evolution of the ground observation availability since 2014. All validation reports are online at <https://atmosphere.copernicus.eu/supplementary-services>.

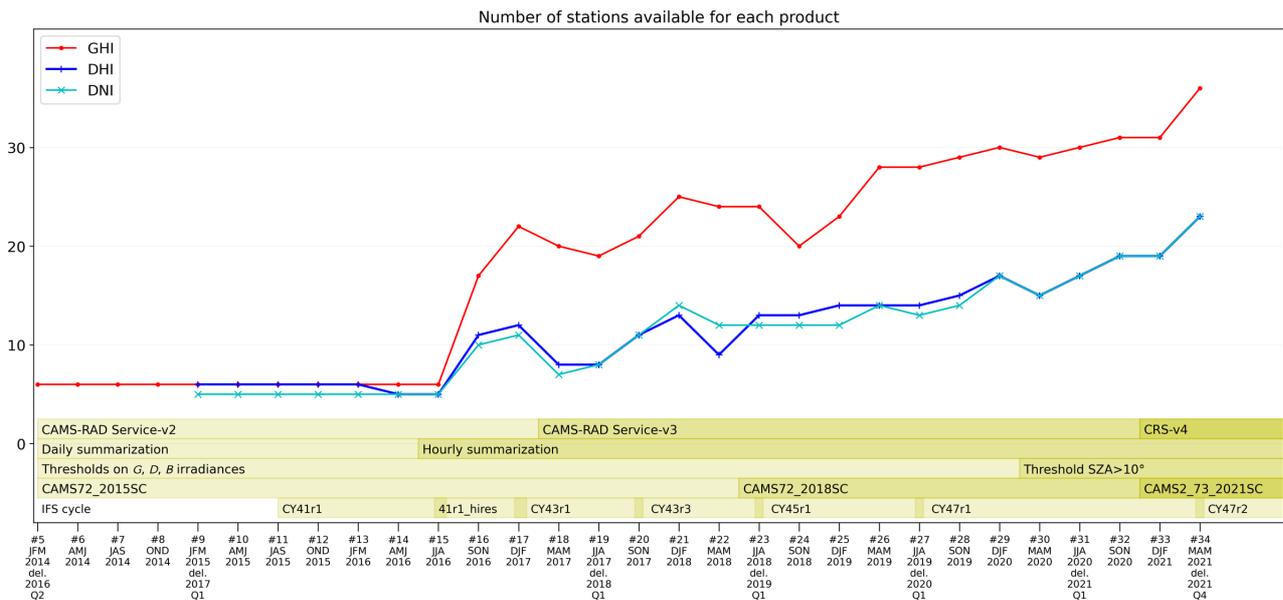


Figure 1.1. Evolution of the number of stations used for each product from 2014.

On the x-axis are the validation reports identified by their issue number, the CAMS Radiation Service version as used in the previously published validation reports, along with the months and years corresponding to the measurements.

## 2 Stations

The source of ground-based measurements is given in section 4, along with a description of each station, its provider, and the products provided:  $G$ ,  $B$ ,  $D$  are global, beam and diffuse irradiances respectively, and  $KT_G$ ,  $KT_B$ ,  $KT_D$  are global, beam and diffuse clearness indices, respectively. These parameters are defined in [Annex A.7](#).

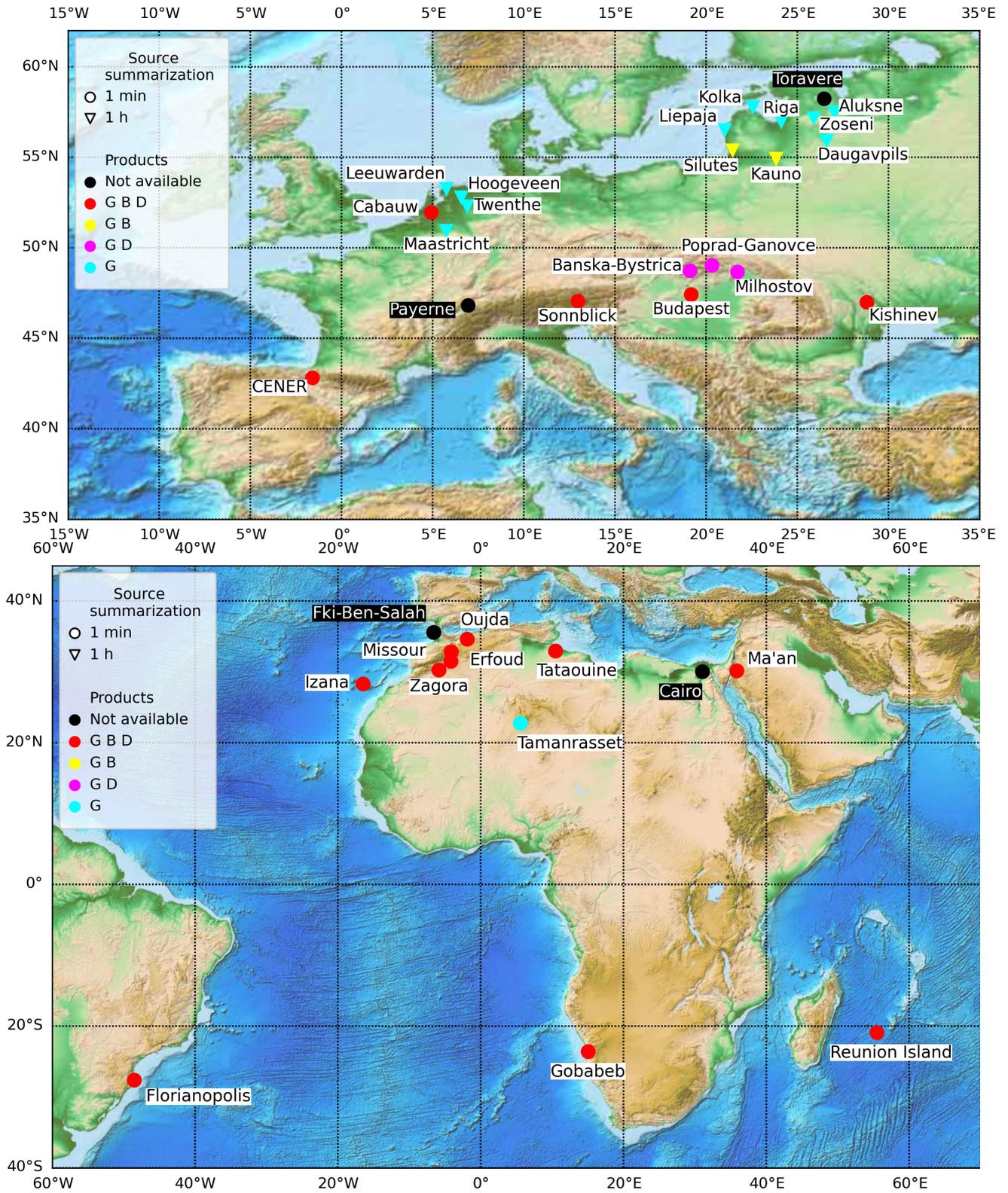
### 2.1 Maps

Figure 2.1 shows the location of the stations as reported in [Table 4.2](#). Symbols code the initial integration time of the data as reported in [Table 4.1](#): circle for 1 min, and downward triangle for 1 h. Colours code the type of data at each site: red for ( $G$ ,  $B$ ,  $D$ ), yellow for ( $G$ ,  $B$ ), magenta for ( $G$ ,  $D$ ) and cyan for  $G$ .



In the #27 report, some stations have been removed from the set of usual stations, and some others have been added (see Fig. 2.3 in #27). Stations too close to the sea like Hoorn (see 4.1.1 in #27 for the report of the problem) and Vlissingen in the Netherlands have been removed and replaced by Leeuwarden and Maastricht (Fig. 2.3). Stations have been closed by the providers like Carpentras and Dobeles in December 2018, Rucava in September 2018, or are not updated regularly like PSA (year 2017 was provisioned in December 2018, years 2018 and 2019 was provisioned in April 2020). New stations offset these removals like CENER in Spain, or Aluksne and Kolka, two stations provided monthly by the Latvian network instead of Dobeles and Rucava. Since November 2019, the enerMENA network provides a new station Fki Ben Salah in Morocco. In the #31 report, the KNMI station of Cabauw has been replaced with the same station provided by the BSRN network that offers the 3 components *G*, *D* and *B* at 1 min of resolution. The BSRN station of Izaña has been added to illustrate restricts for validation at a mountain top with restricted representativity for its surroundings. In the #32 report, the new BSRN stations of Budapest and Reunion Island have been added.

In this #34 issue, the BSRN stations Granite Island and Langley in United States, Syowa in Antarctica, and Ny-Ålesund in Spitzbergen have been added for the validation of McClear outside the satellite field of view. They come along with station Tateno added in the #33 issue. Such stations will be further integrated.



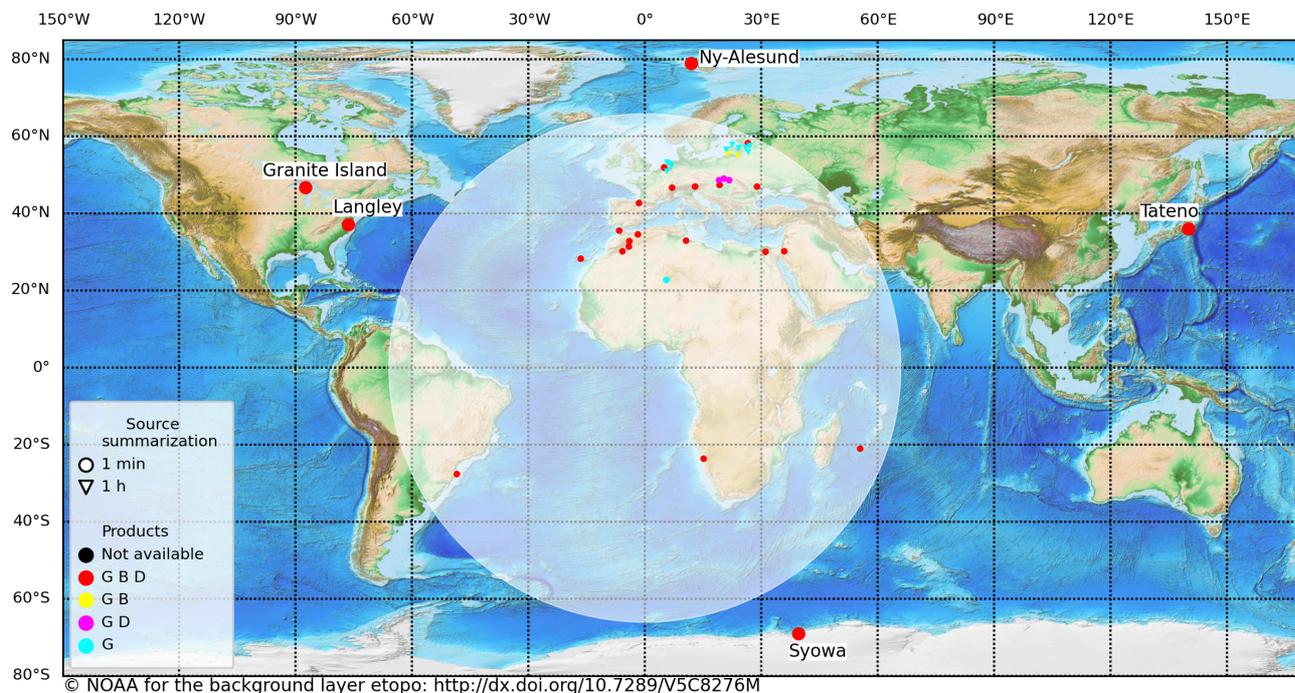


Figure 2.1. Maps showing the 35 stations inside the satellite field of view: 22 stations in Europe (top), 13 stations outside Europe (middle) and 5 stations outside the satellite field of view (bottom). Symbols code the initial integration time: circle for 1 min, and downward triangle for 1 h. Colours code the type of data at each site: red for (G, B, D), yellow for (G, B), magenta for (G, D) and cyan for G.

## 2.2 List of the stations retained for this quarter

Depending on the provision of fresh data, possible problems affecting measuring instruments, possible rejection of some data by the quality control, and other causes, it is not always possible to use the same set of stations to perform the quarterly validation. [Table 2.1](#) lists the 36 stations that have been retained for this quarter, along with the 4 stations having no available data for this quarter. More details on the stations and their providers are presented in [Table 4.1](#) in the [section 4](#) “Sources of data”.

Due to low satellite viewing angles, lower CRS quality is expected for stations in Lettland and Lithuania (Aluksne, Daugavpils, Kauno, Kolka, Liepaja, Riga, Silutes, Toravere) and Brazil (Florianopolis). Nevertheless, stations in Lettland and Lithuania provide some insight on the area where the CRS may become unreliable and therefore, this information is kept in this user-oriented report. The same reason motivates the addition of Izaña and Sonnblick at mountain tops and not representative for their surroundings.

A summary of the quality check operated on each station is given in [Table 2.2](#) (section 2.3).



Table 2.1. List of stations retained or excluded for this regular validation report, along with the number of hourly samples for global (*G*), diffuse (*D*) and beam (*B*) components remaining after the quality check process, the solar zenith angle threshold, and the selection of cloud-free instants for McClear.

Station	Provider ( <a href="#">Table 4.1</a> )	Nb of 1 h samples		Issue for the period
		all sky	cloud free	
Aluksne	LEGMC	G:629 D: --- B: ---	<i>Unavailable</i>	Reduced service accuracy expected due to low satellite viewing angle.
Banska-Bystrica	SHMI	G:1046 D:1046 B: ---	G+D: 55	
Budapest	BSRN	G:1044 D:1044 B:1045	G+D+B: 83	
Cabauw	BSRN	G:1005 D:1005 B:1006	G+D+B: 31	
<i>Cairo</i>	<i>enerMENA</i>	<i>G: --- D: --- B: ---</i>	<i>G+D+B: ---</i>	tracker broken --> Only GHI data accurate. <b>Station doubtfully maintained, eliminated by the quality check (see <a href="#">§ 4.4.1</a>).</b>
CENER	BSRN	G:1022 D:1022 B:1026	G+D+B: 81	
Daugavpils	LEGMC	G:632 D: --- B: ---	<i>Unavailable</i>	Reduced service accuracy expected due to low satellite viewing angle.
Erfoud	enerMENA	G:1036 D:1036 B:1036	G+D+B: 182	Good quality
<i>Fki Ben Salah</i>	<i>enerMENA</i>	<i>G: --- D: --- B: ---</i>	<i>G+D+B: ---</i>	<i>G</i> data not available. <i>D</i> data good quality. DNI pyrheliometer sometimes misaligned in the morning. Pb sensor blocked. Maintenance visit and installation of new wind vane in Feb. <b>Station eliminated by the quality check in the absence of <i>G</i> (see <a href="#">§ 4.4.5</a>).</b>
Florianopolis	BSRN	G:333 D:333 B:333	<i>G+D+B: 2</i>	Reduced service accuracy expected due to low satellite viewing angle. <b>No data available since April 2021.</b>
Gobabeb	BSRN	G:922 D:922 B:922	G+D+B: 356	
Granite Island	BSRN	<i>Unavailable</i>	G+D+B: 117	<b>New station outside satellite field of view.</b>
Hoogeveen	KNMI	G:1042 D: --- B: ---	<i>Unavailable</i>	
Izaña	BSRN	G:1031 D:1031 B:1033	G+D+B: 223	Reduced service accuracy expected due to altitude 2372 m and its location at a mountain top.



Station	Provider (Table 4.1)	Nb of 1 h samples		Issue for the period
		all sky	cloud free	
Kauno	LHMS	G:1048 D: --- B:1048	<i>Unavailable</i>	Reduced service accuracy expected due to low satellite viewing angle.
Kishinev	WRDC	G:1028 D:1028 B:1028	<i>Unavailable</i>	
Kolka	LEGMC	G:629 D: --- B: ---	<i>Unavailable</i>	Reduced service accuracy expected due to low satellite viewing angle.
Langley	BSRN	<i>Unavailable</i>	G+D+B: 144	<b>New station outside satellite field of view.</b>
Leeuwarden	KNMI	G:1041 D: --- B: ---	<i>Unavailable</i>	
Liepaja	LEGMC	G:632 D: --- B: ---	<i>Unavailable</i>	Reduced service accuracy expected due to low satellite viewing angle.
Ma'an	enerMENA	G:988 D:988 B:995	G+D+B: 326	Quality ok. Tracker unaligned in the morning.
Maastricht	KNMI	G:1046 D: --- B: ---	<i>Unavailable</i>	
Milhostov	SHMI	G:1027 D:1027 B: ---	G+D: 67	
Missour	enerMENA	G:983 D:983 B:989	G+D+B: 148	Good quality. Week-daily cleaning. Tracker off in April until 14 <sup>th</sup> .
Ny-Ålesund	BSRN	<i>Unavailable</i>	G+D+B: 93	<b>New station outside satellite field of view.</b>
Oujda	enerMENA	G:446 D:446 B:456	G+D+B: 60	Good quality in March. Tracker off in April and May; only GHI available. Cleaning every ~3 days.
<i>Payerne</i>	<i>BSRN</i>	<i>G: --- D: --- B: ---</i>	<i>: ---</i>	No data available from February 2020 onwards.
Poprad-Ganovce	SHMI	G:1047 D:1047 B:1048	G+D+B: 51	
Reunion Island	BSRN	G:934 D:934 B:935	G+D+B: 52	
Riga	LEGMC	G:629 D: --- B: ---	<i>Unavailable</i>	Reduced service accuracy expected due to low satellite viewing angle.
Silutes	LHMS	G:1041 D: --- B:1041	<i>Unavailable</i>	Reduced service accuracy expected due to low satellite viewing angle.
Sonnblick	BSRN	G:1019 D:1019 B:1024	G+D+B: 91	Reduced service accuracy expected due to altitude 3109 m and its location at a mountain top.
Syowa	BSRN	<i>Unavailable</i>	G+D+B: 40	<b>New station outside satellite field of view.</b>
Tamanrasset	BSRN	G:995 D: --- B: ---	<i>Unavailable</i>	Only <i>G</i> is available. <i>D</i> and <i>B</i> unavailable from March 2018 onwards.
Tataouine	enerMENA	G:1033 D:1033 B:1033	G+D+B: 128	Good quality, cleaning every ~3days.
Tateno	BSRN	<i>Unavailable</i>	G+D+B: 57	



Station	Provider (Table 4.1)	Nb of 1 h samples		Issue for the period
		all sky	cloud free	
Toravere	BSRN	G: --- D: --- B: ---	: ---	<b>No data available from June 2020 onwards.</b> Reduced service accuracy expected due to low satellite viewing angle.
Twenthe	KNMI	G:1044 D: --- B: ---	Unavailable	
Zagora	enerMENA	G:333 D:333 B:333	G+D+B: 71	Good quality.
Zoseni	LEGMC	G:629 D: --- B: ---	Unavailable	Reduced service accuracy expected due to low satellite viewing angle.

## 2.3 Quality check

Table 2.2 summarizes for each station:

- The number of usable values in the ground dataset expressed as a percentage of the number of daylight instants in the MAM period, i.e., the number of instants corresponding to the source resolution (1 h or 1 min) for a solar zenith angle  $SZA \leq 89^\circ$ .
- The number of values rejected by the quality check (QC) expressed as a percentage of the usable values in the ground dataset.
- The number of retained values in the ground dataset after the quality check, expressed as a percentage of the number of daylight instants in the MAM 2021 period. That represents the dimension of the ground dataset before the integration time to hourly resolution and the application of the SZA threshold.

Table 2.2. Quantities of ground measurements rejected or retained for each station in the MAM 2021 period.

Station	Variable	Daylight instants during MAM 2021	Observation $\geq 0 \text{ W m}^{-2}$ during daylight before QC		QC Test	Data rejected by the QC during daylight		Observation $\geq 0 \text{ W m}^{-2}$ during daylight after QC and before SZA threshold	
			N	%		N	%	N	%
Aluksne	G	1261	766	60.7	BSRN-1C	0	0.000	766	60.7
Banska-Bystrica	G	73139	73130	100.0	BSRN-2C	2	0.003	73119	100.0



Station	Variable	Daylight instants during MAM 2021	Observation $\geq 0 \text{ W m}^{-2}$ during daylight before QC		QC Test	Data rejected by the QC during daylight		Observation $\geq 0 \text{ W m}^{-2}$ during daylight after QC and before SZA threshold	
			N	N		%	N	%	N
	D		73127	100.0		6	0.008	73119	100.0
Budapest	G	72796	72511	99.6	BSRN-3C	633	0.873	70131	96.3
	B		70517	96.9		171	0.242	70131	96.3
	D		72545	99.7		633	0.873	70131	96.3
CENER	G	71711	71678	100.0	BSRN-3C	88	0.123	68686	95.8
	B		68783	95.9		88	0.128	68686	95.8
	D		71680	100.0		88	0.123	68686	95.8
Cabauw	G	74100	73941	99.8	BSRN-3C	63	0.085	70136	94.7
	B		71006	95.8		51	0.072	70136	94.7
	D		71132	96.0		71	0.100	70136	94.7
Cairo									
Daugavpils	G	1256	762	60.7	BSRN-1C	0	0.000	762	60.7
Erfoud	G	69625	69624	100.0	BSRN-3C	0	0.000	69598	100.0
	B		69624	100.0		0	0.000	69598	100.0
	D		69624	100.0		26	0.037	69598	100.0
Fki Ben Salah									
Florianopolis	G	61699	22010	35.7	BSRN-3C	0	0.000	21684	35.1
	B		21760	35.3		0	0.000	21684	35.1
	D		21963	35.6		29	0.132	21684	35.1
Gobabeb	G	62368	61951	99.3	BSRN-3C	16	0.026	61831	99.1
	B		62269	99.8		12	0.019	61831	99.1
	D		62339	100.0		16	0.026	61831	99.1
Granite Island	G	72607	68611	94.5	BSRN-3C	129	0.188	68122	93.8
	B		68586	94.5		120	0.175	68122	93.8
	D		71942	99.1		121	0.168	68122	93.8
Hoogeveen	G	1231	1231	100.0	BSRN-1C	0	0.000	1231	100.0
Izana	G	69137	67409	97.5	BSRN-3C	27	0.040	67070	97.0
	B		67715	97.9		26	0.038	67070	97.0
	D		67423	97.5		27	0.040	67070	97.0
Kauno	G	1252	1252	100.0	BSRN-1C	1	0.080	1251	99.9
	B		1252	100.0		16	1.278	1236	98.7
Kishinev	G	1209	1208	99.9	BSRN-3C	17	1.407	1188	98.3
	B		1208	99.9		36	2.980	1172	96.9



Station	Variable	Daylight instants during MAM 2021	Observation $\geq 0 \text{ W m}^{-2}$ during daylight before QC		QC Test	Data rejected by the QC during daylight		Observation $\geq 0 \text{ W m}^{-2}$ during daylight after QC and before SZA threshold	
			N	%		N	%	N	%
	D		1208	99.9		19	1.573	1188	98.3
Kolka	G	1264	767	60.7	BSRN-1C	0	0.000	767	60.7
Langley	G	70614	70094	99.3	BSRN-3C	150	0.214	66298	93.9
	B		66748	94.5		148	0.222	66298	93.9
	D		70286	99.5		153	0.218	66298	93.9
Leeuwarden	G	1237	1237	100.0	BSRN-1C	0	0.000	1237	100.0
Liepaja	G	1258	764	60.7	BSRN-1C	0	0.000	764	60.7
Ma'an	G	69405	69269	99.8	BSRN-3C	414	0.598	66856	96.3
	B		69269	99.8		356	0.514	66856	96.3
	D		68559	98.8		1703	2.484	66856	96.3
Maastricht	G	1226	1226	100.0	BSRN-1C	1	0.082	1225	99.9
Milhostov	G	73114	71979	98.4	BSRN-2C	0	0.000	71722	98.1
	D		71729	98.1		7	0.010	71722	98.1
Missour	G	69849	69810	99.9	BSRN-3C	899	1.288	63752	91.3
	B		69810	99.9		894	1.281	63752	91.3
	D		67418	96.5		3664	5.435	63752	91.3
Ny-Ålesund	G	99088	97469	98.4	BSRN-3C	432	0.443	89908	90.7
	B		90780	91.6		273	0.301	89908	90.7
	D		97853	98.8		426	0.435	89908	90.7
Oujda	G	70146	30185	43.0	BSRN-3C	0	0.000	29556	42.1
	B		30596	43.6		0	0.000	29556	42.1
	D		29592	42.2		0	0.000	29556	42.1
Payerne									
Poprad-Ganovce	G	73222	73205	100.0	BSRN-3C	100	0.137	71611	97.8
	B		71742	98.0		87	0.121	71611	97.8
	D		73178	99.9		119	0.163	71611	97.8
Reunion Island	G	62772	62549	99.6	BSRN-3C	35	0.056	61868	98.6
	B		62117	99.0		3	0.005	61868	98.6
	D		62306	99.3		35	0.056	61868	98.6
Riga	G	1262	765	60.6	BSRN-1C	0	0.000	765	60.6
Silutes	G	1255	1255	100.0	BSRN-1C	0	0.000	1255	100.0
	B		1255	100.0		21	1.673	1234	98.3
Sonnblick	G	72704	67168	92.4	BSRN-3C	351	0.523	62953	86.6



Station	Variable	Daylight instants during MAM 2021	Observation $\geq 0 \text{ W m}^{-2}$ during daylight before QC		QC Test	Data rejected by the QC during daylight		Observation $\geq 0 \text{ W m}^{-2}$ during daylight after QC and before SZA threshold	
			N	%		N	%	N	%
	B		69564	95.7		16	0.023	62953	86.6
	D		66926	92.1		3455	5.162	62953	86.6
Syowa	G	40826	36746	90.0	BSRN-3C	24	0.065	33770	82.7
	B		34863	85.4		0	0.000	33770	82.7
	D		35489	86.9		225	0.634	33770	82.7
Tamanrasset	G	68339	68244	99.9	BSRN-1C	0	0.000	68244	99.9
Tataouine	G	69855	69847	100.0	BSRN-3C	55	0.079	69761	99.9
	B		69847	100.0		54	0.077	69761	99.9
	D		69826	100.0		65	0.093	69761	99.9
Tateno	G	70423	48679	69.1	BSRN-3C	0	0.000	48094	68.3
	B		48094	68.3		0	0.000	48094	68.3
	D		48679	69.1		0	0.000	48094	68.3
Toravere									
Twenthe	G	1229	1229	100.0	BSRN-1C	0	0.000	1229	100.0
Zagora	G	69431	21794	31.4	BSRN-3C	0	0.000	21792	31.4
	B		21794	31.4		0	0.000	21792	31.4
	D		21794	31.4		2	0.009	21792	31.4
Zoseni	G	1262	766	60.7	BSRN-1C	0	0.000	766	60.7
	D		35489	86.9		225	0.634	33770	82.7
Tamanrasset	G	68339	68244	99.9	BSRN-1C	0	0.000	68244	99.9

### 3 Overview of the results

Following the ISO standard (1995), the deviations are computed by subtracting observations for each instant from the product estimations (CRS - measurements), and are summarized by usual statistical quantities such as the bias or the root mean square error. The validation procedure is described in Annex A. The selection of the cloud-free instants for the validation of McClear is described in Annex A.8. Detailed results for the report's season are given for each station in Annexes B.



### 3.1 Bias and standard deviation of errors

Detailed tables for the MAM 2021 quarter summarize the performance of the CRS for hourly means of global irradiance (in  $W m^{-2}$ , Tab. 3.1), corresponding clearness index (Tab. 3.2), and the performances relative to the mean of measurements (in percent, Tab. 3.3). Similar detailed tables are given for the *D* component (Tab. 3.4 to 3.6) and the *B* component (Tab. 3.7 to 3.9). They are available as an excel file in a folder of the supplemental zip archive:

[CAMS2\\_73\\_2021SC1\\_D1.3.1-2021Q4\\_section3\\_statistical\\_metrics/CAMS2\\_73\\_2021SC1\\_D1.3.1-2021Q4\\_section3\\_statistical\\_metrics\\_MAM2021.xlsx](#)

Table 3.1 summarizes the performance of CRS for the hourly mean of irradiances. The following empirical rules adopted for the bias are derived from the uncertainty ( $20 W m^{-2}$ ) of the measurements of hourly irradiation of good quality from the recommendations of the WMO (see [Annex A.6](#)).

Table 3.1. Number of stations in each category of bias (in  $W m^{-2}$ )

Rules for the bias (in $W m^{-2}$ )		CAMS-RAD		McClear	
		<i>G</i>	<i>D</i>	<i>G</i>	<i>D</i>
Null bias	Absolute value of the bias $\leq 5$	4	7	4	0
Low bias	$5 <$ absolute value of the bias $\leq 10$	9	4	5	1
Noticeable bias	$10 <$ absolute value of the bias $\leq 20$	11	3	9	4
Large bias	$20 <$ absolute value of the bias $\leq 60$	5	3	3	11
Very large bias	absolute value of the bias $> 60$	2	1	0	5
Total stations with nb of obs. $> 30$		30	31	18	21

Relative biases and RMSE are given in Figures 3.1, 3.2 and 3.3 for respectively *G*, *D* and *B*.

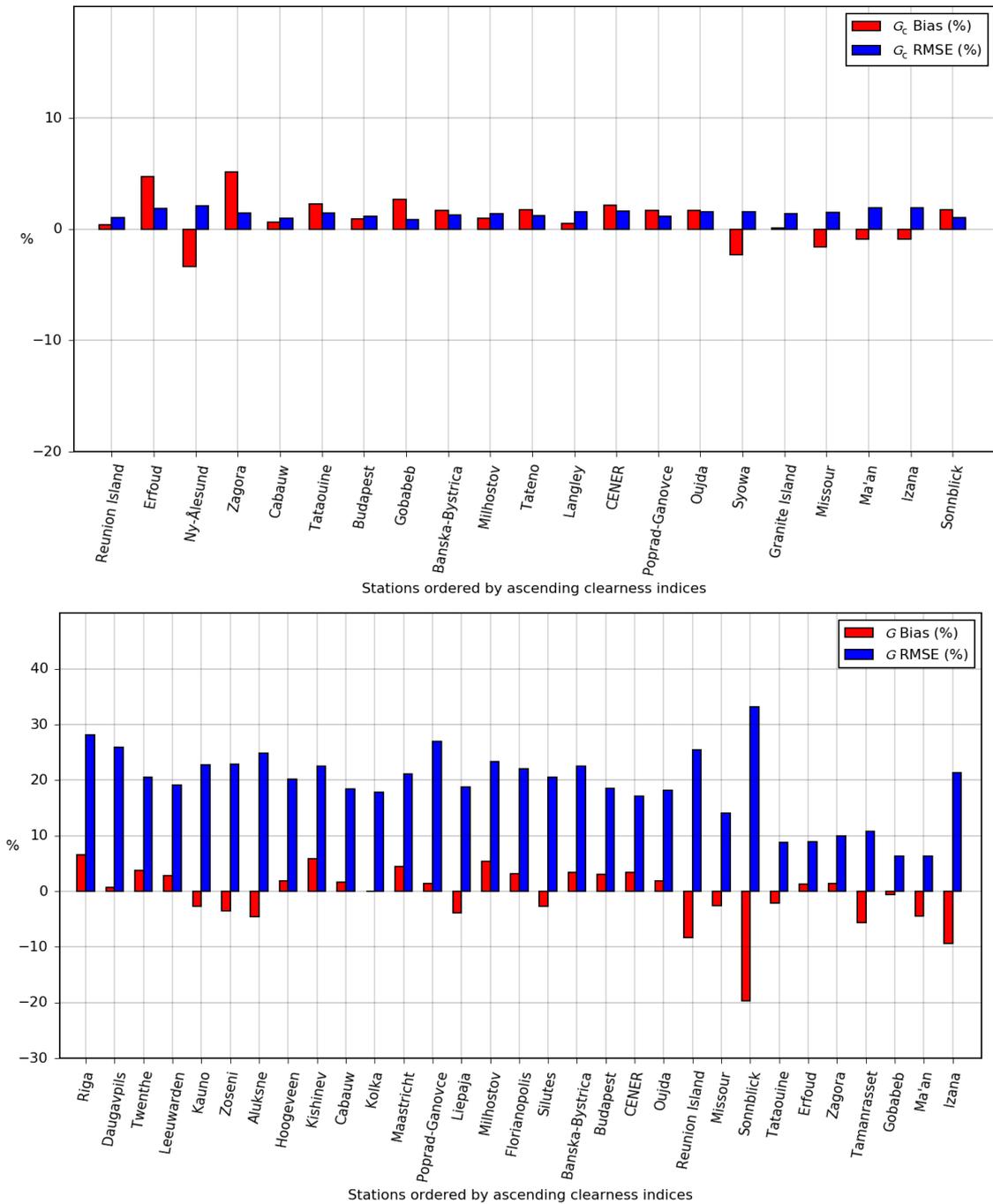


Figure 3.1. Relative bias and RMSE for global irradiance. Top: McClear. Bottom: CAMS-RAD.

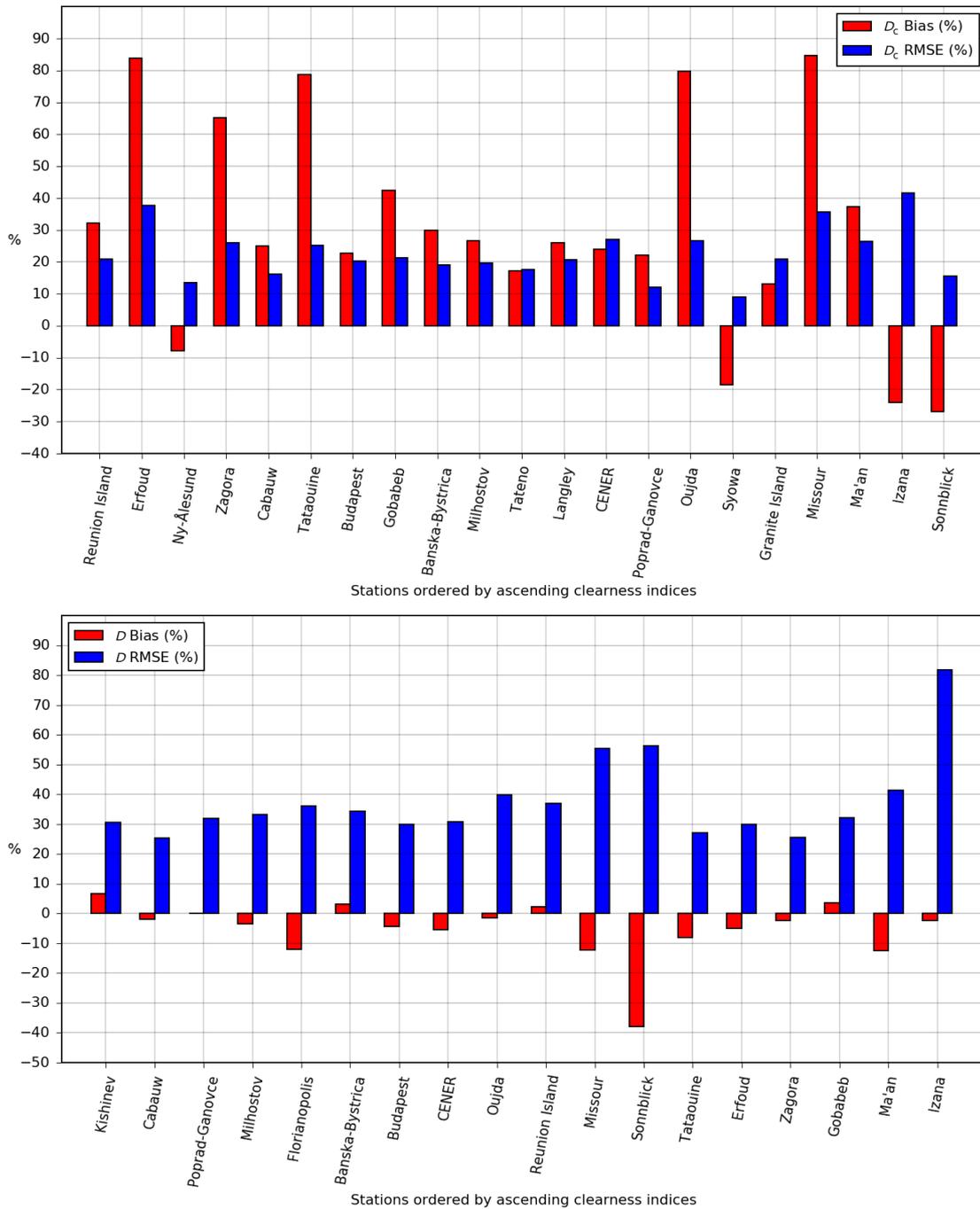


Figure 3.2. Relative bias and RMSE for diffuse irradiance. Top: McClear. Bottom: CAMS-RAD.

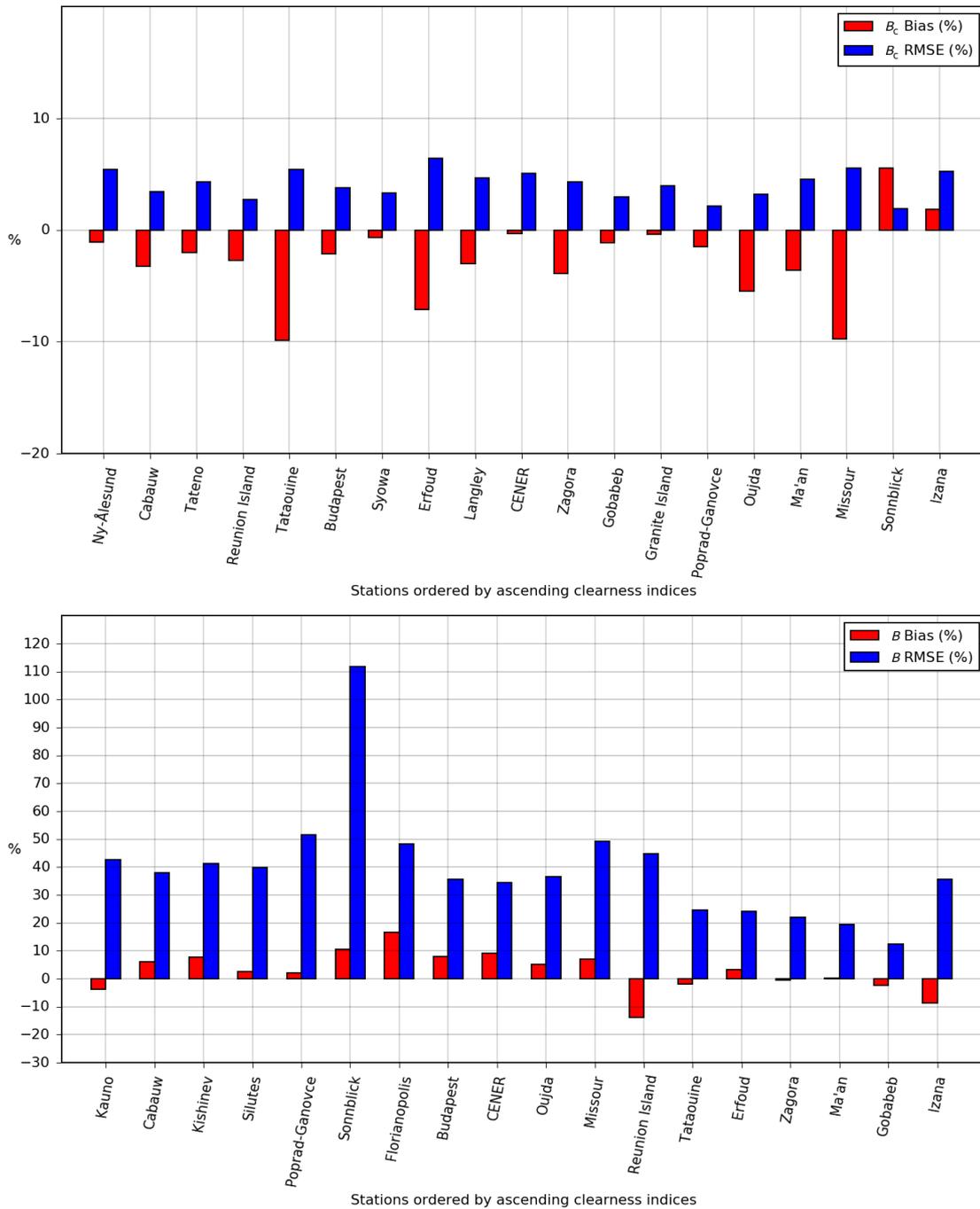


Figure 3.3. Relative bias and RMSE for direct irradiance. Top: McClear. Bottom: CAMS-RAD.



### 3.2 Ability to reproduce the intra-day variability

The correlation coefficients of the MAM 2021 quarter are displayed for irradiances and clearness indices:  $G$  and  $KT_G$  (Fig. 3.4),  $D$  and  $KT_D$  (Fig. 3.5),  $B$  and  $KT_B$  (Fig. 3.6).

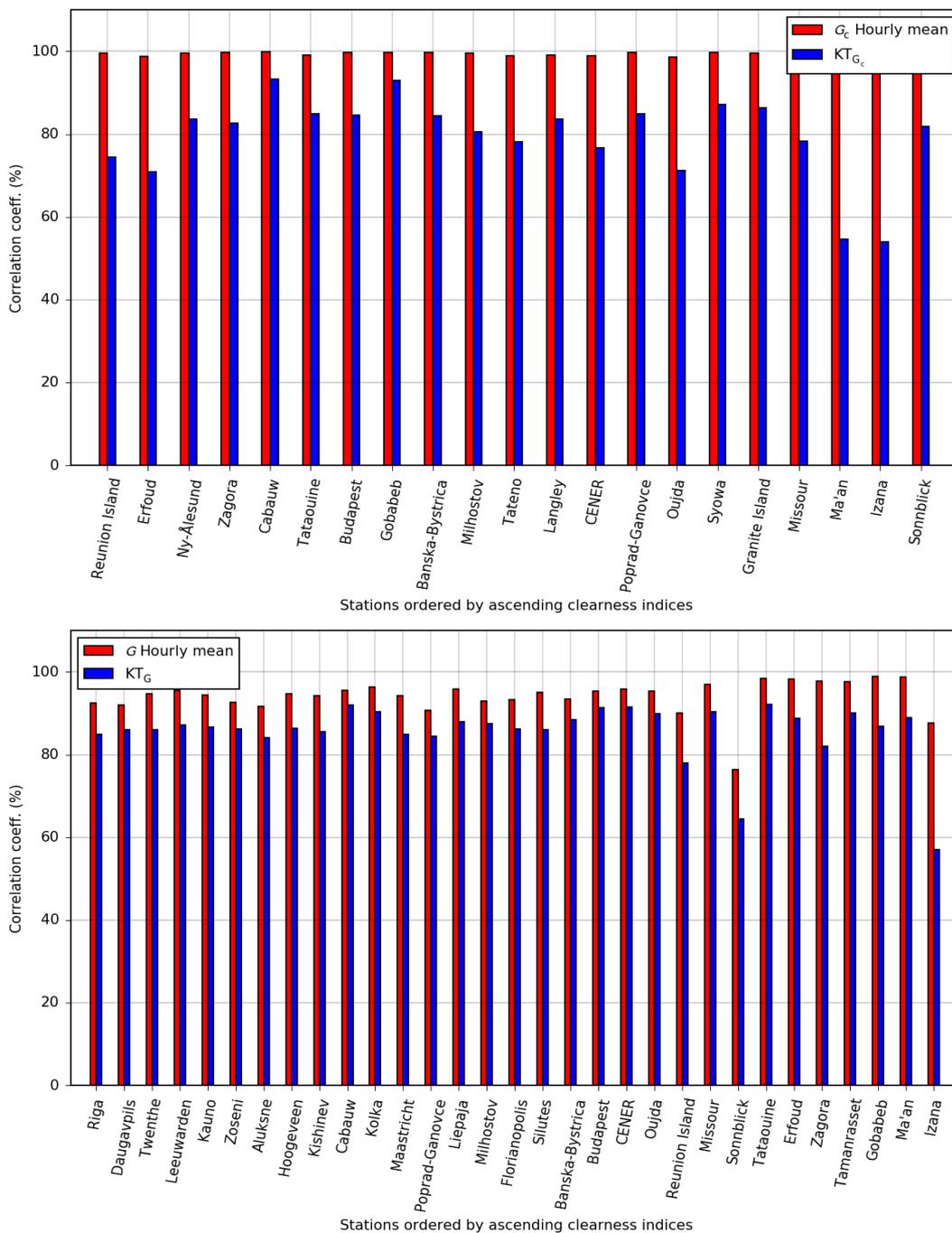


Figure 3.4. Correlation coefficients for global irradiance and clearness index.



Top: McClear. Bottom: CAMS-RAD.

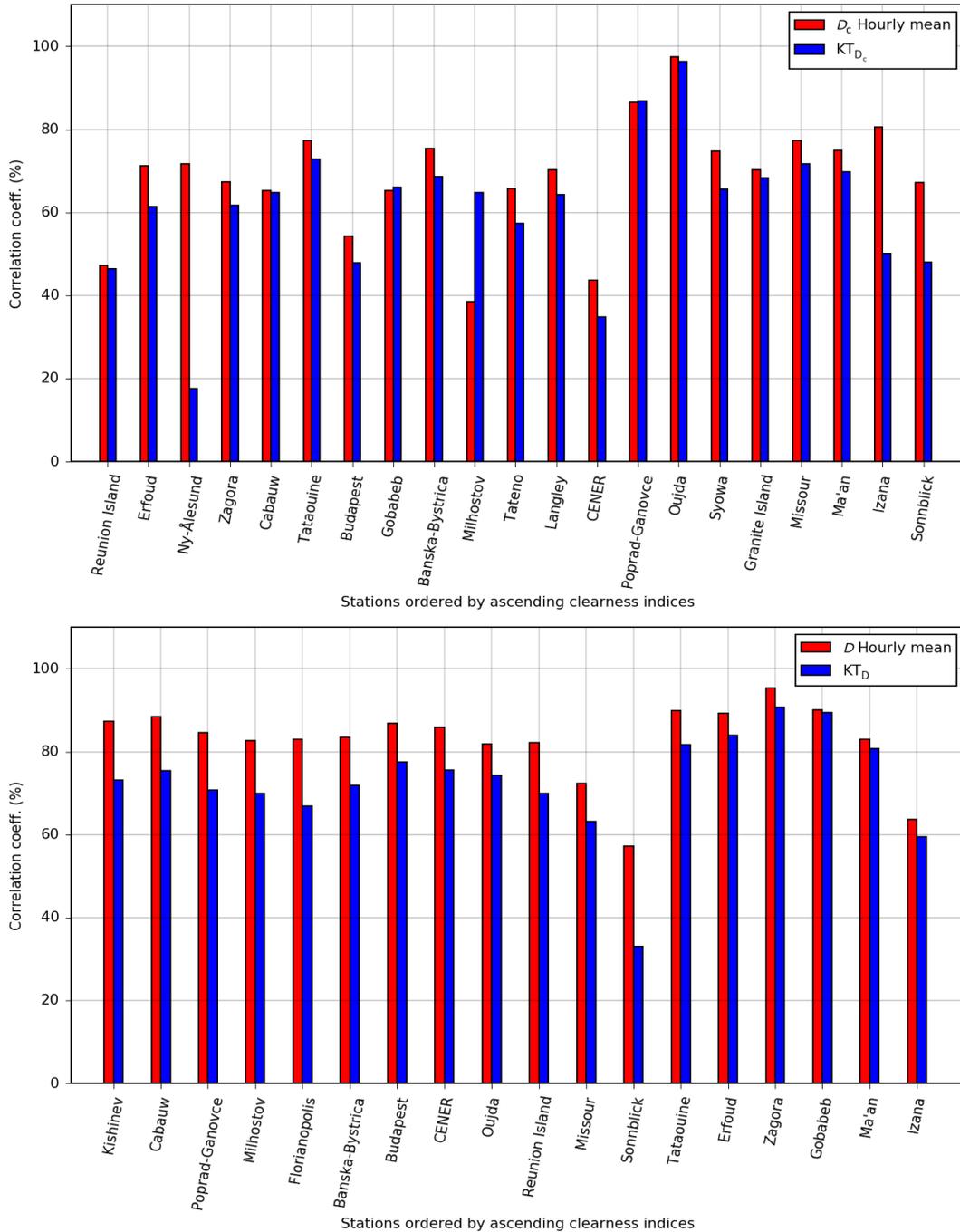


Figure 3.5. Correlation coefficients for diffuse irradiance and clearness index. Top: McClear. Bottom: CAMS-RAD.

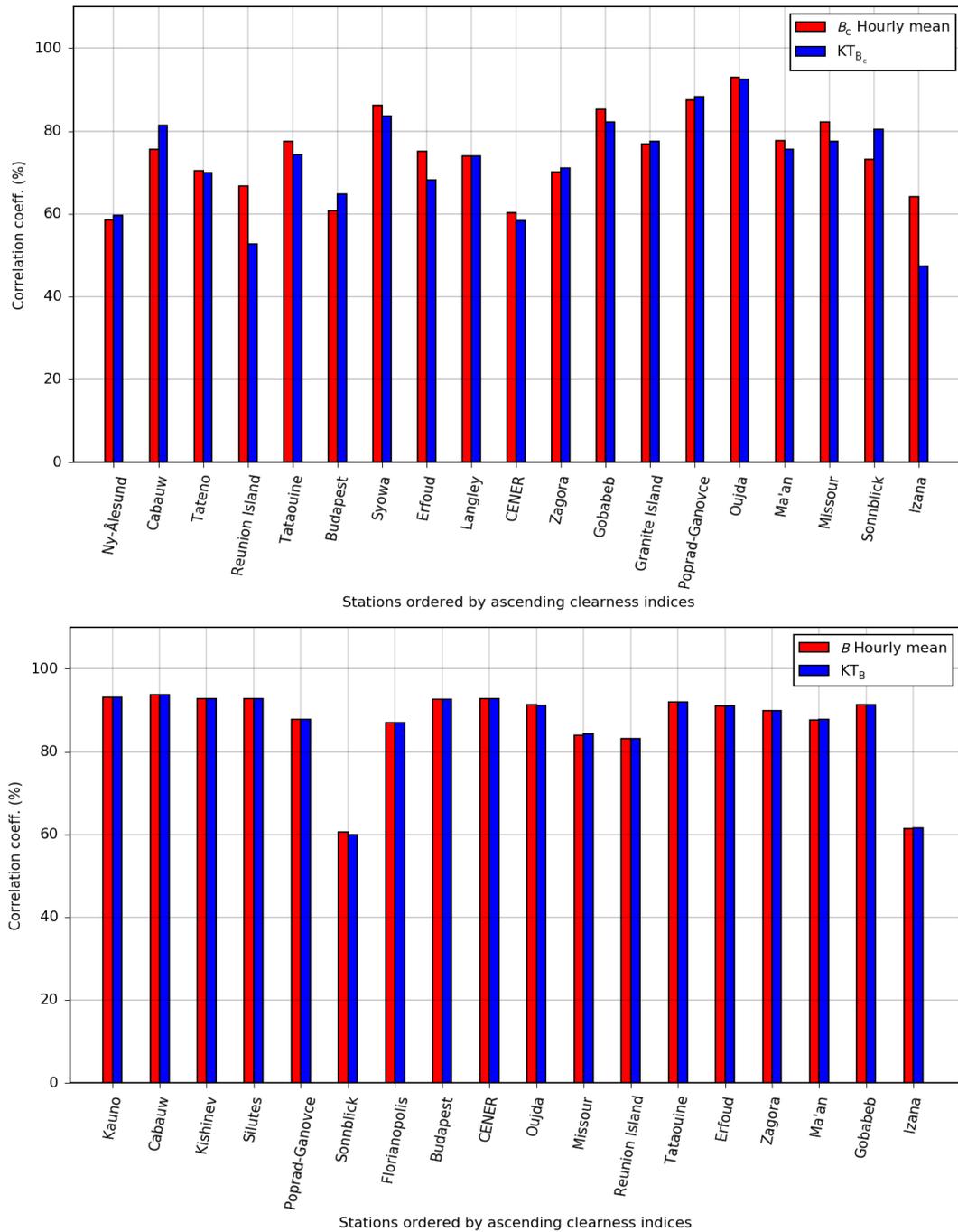


Figure 3.6. Correlation coefficients for direct normal irradiance and clearness index. Top: McClea. Bottom: CAMS-RAD.



### 3.3 Ability to reproduce the frequency distributions of measurements

The frequency distributions of  $G$  and  $KT_G$  (Fig. 3.7 and 3.8),  $D$  and  $KT_D$  (Fig. 3.9 and 3.10),  $B$  and  $KT_B$  (Fig. 3.11 and 3.12) are given for several classes of irradiances or  $KT$ . The objective of these figures is to display in which bins of values an over- or underestimation of the frequencies may be observed.

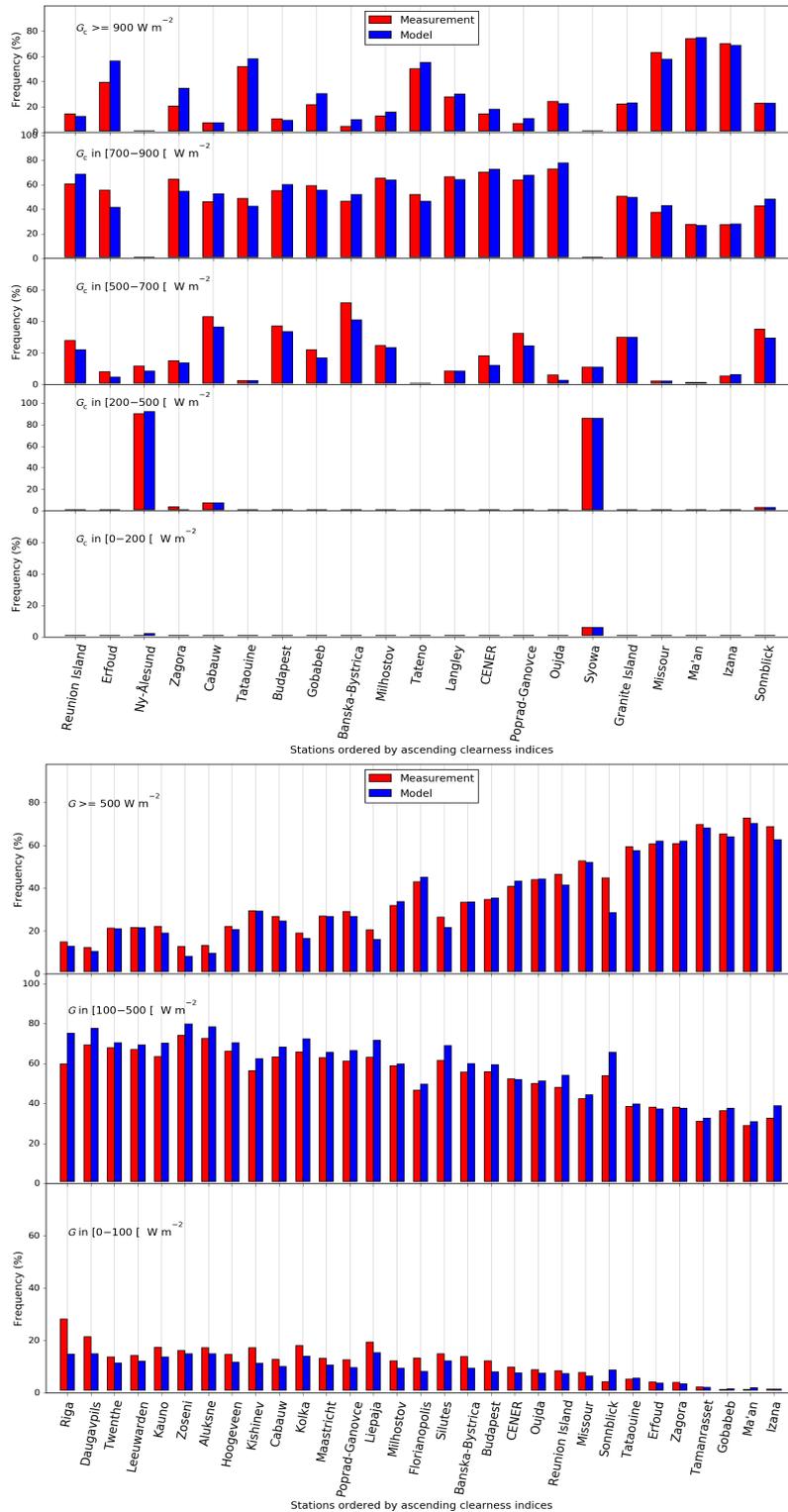


Figure 3.7. Frequency distribution of measurements for global irradiance. Top: McClear. Bottom: CAMS-RAD.

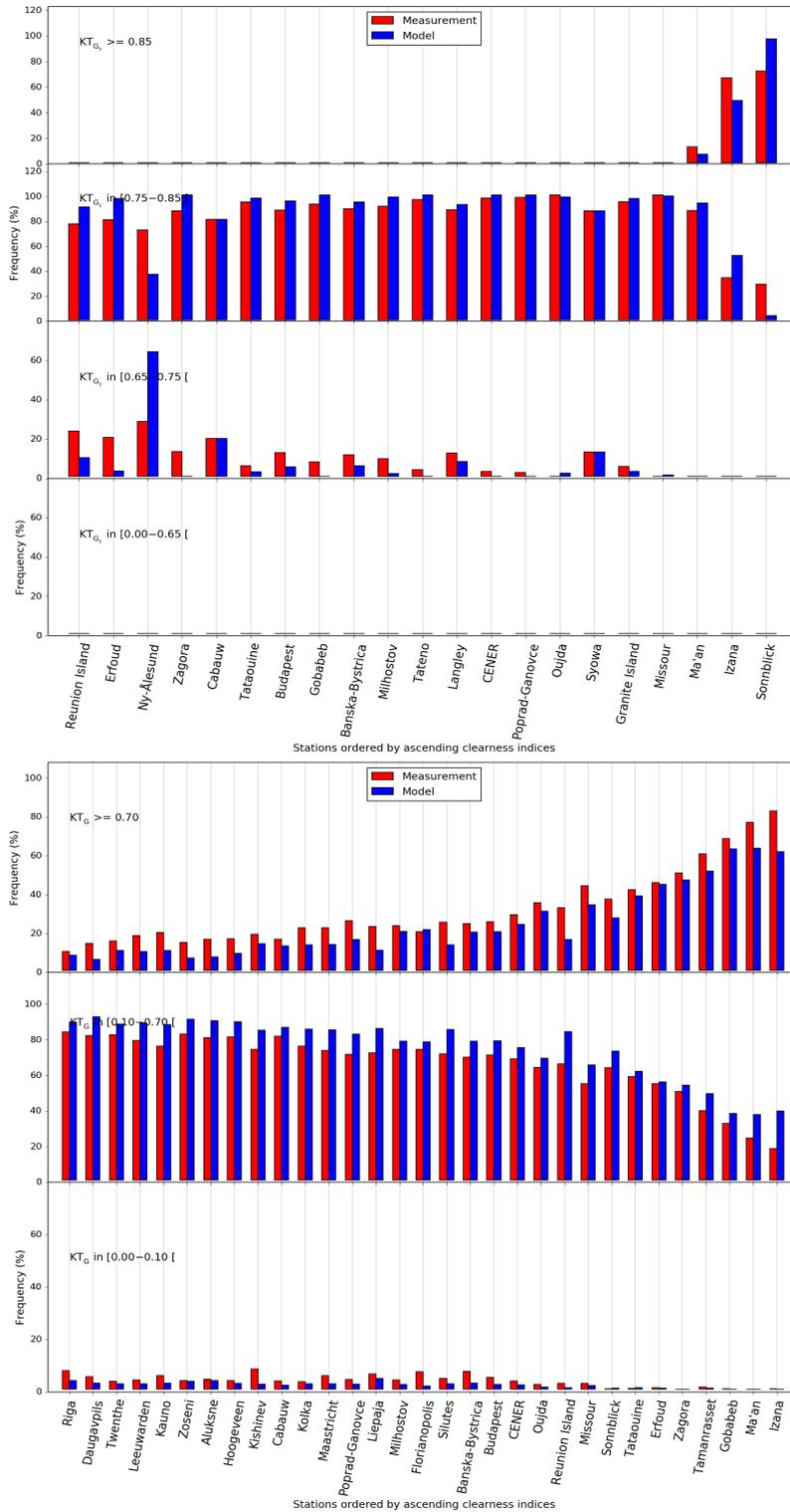


Figure 3.8. Frequency distribution of measurements for global clearness index. Top: McClear. Bottom: CAMS-RAD.

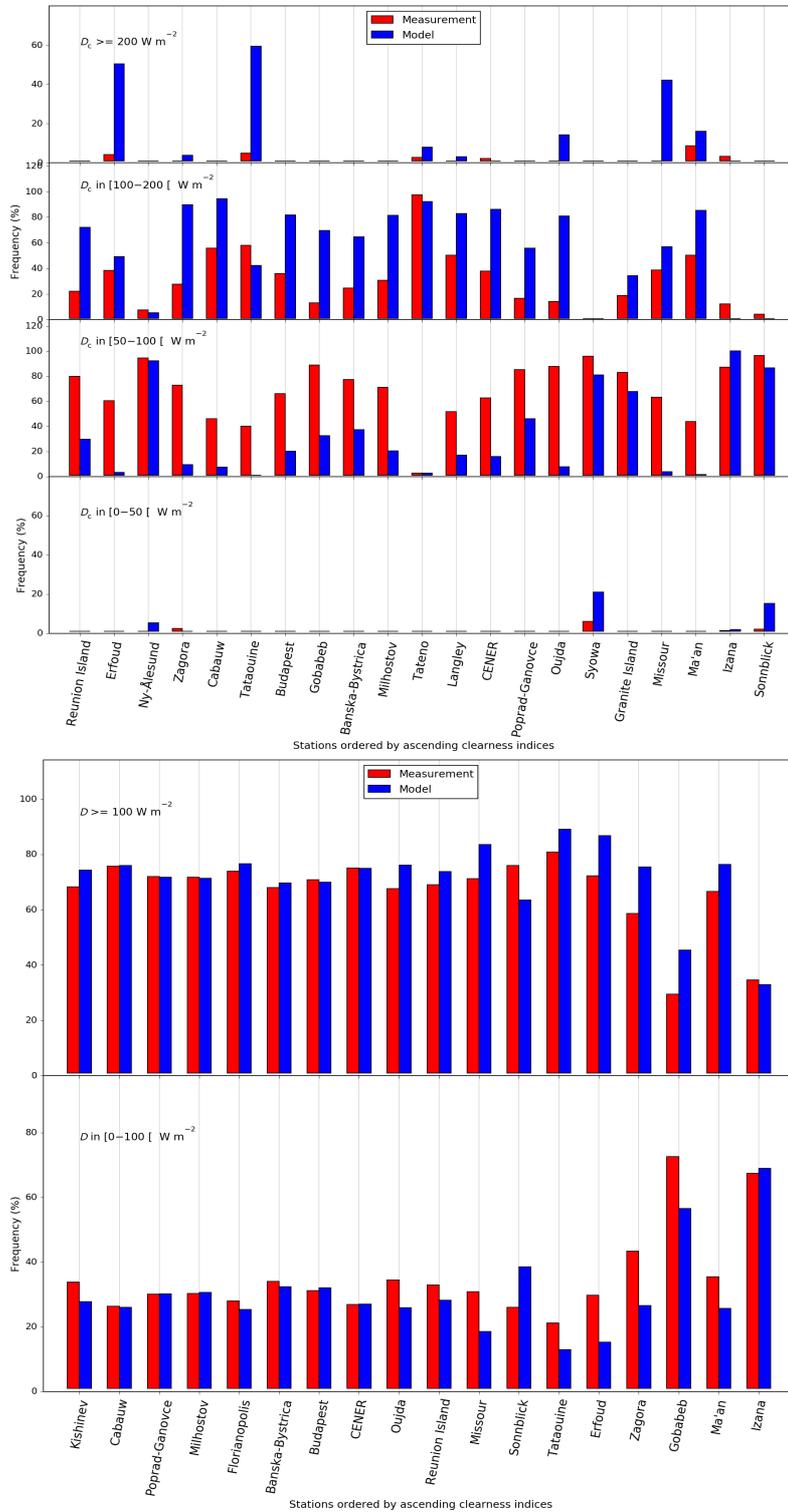


Figure 3.9. Frequency distribution of measurements for diffuse irradiances. Top: McClear. Bottom: CAMS-RAD.

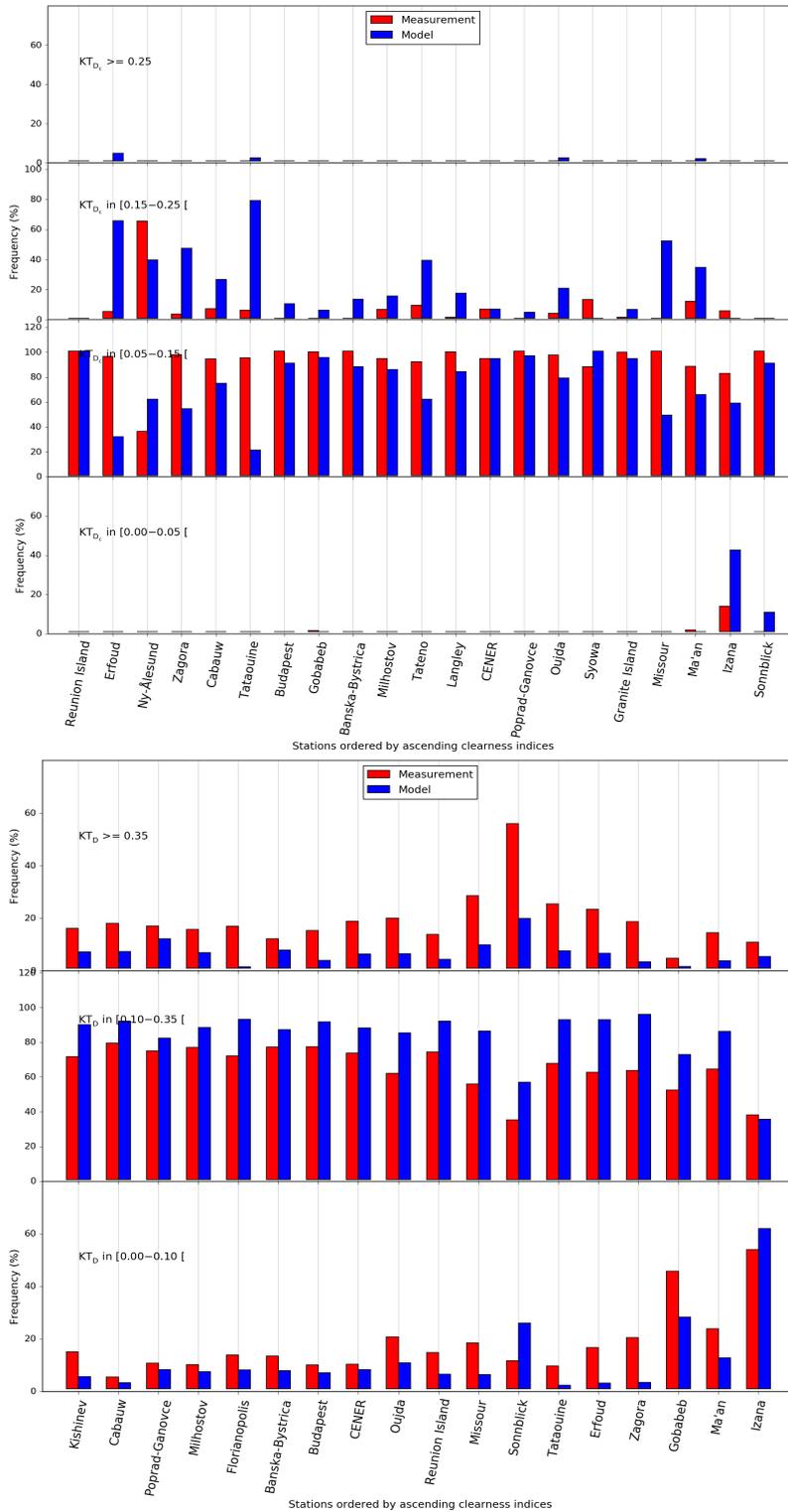


Figure 3.10. Frequency distribution of measurements for diffuse clearness index. Top: McClear. Bottom: CAMS-RAD.

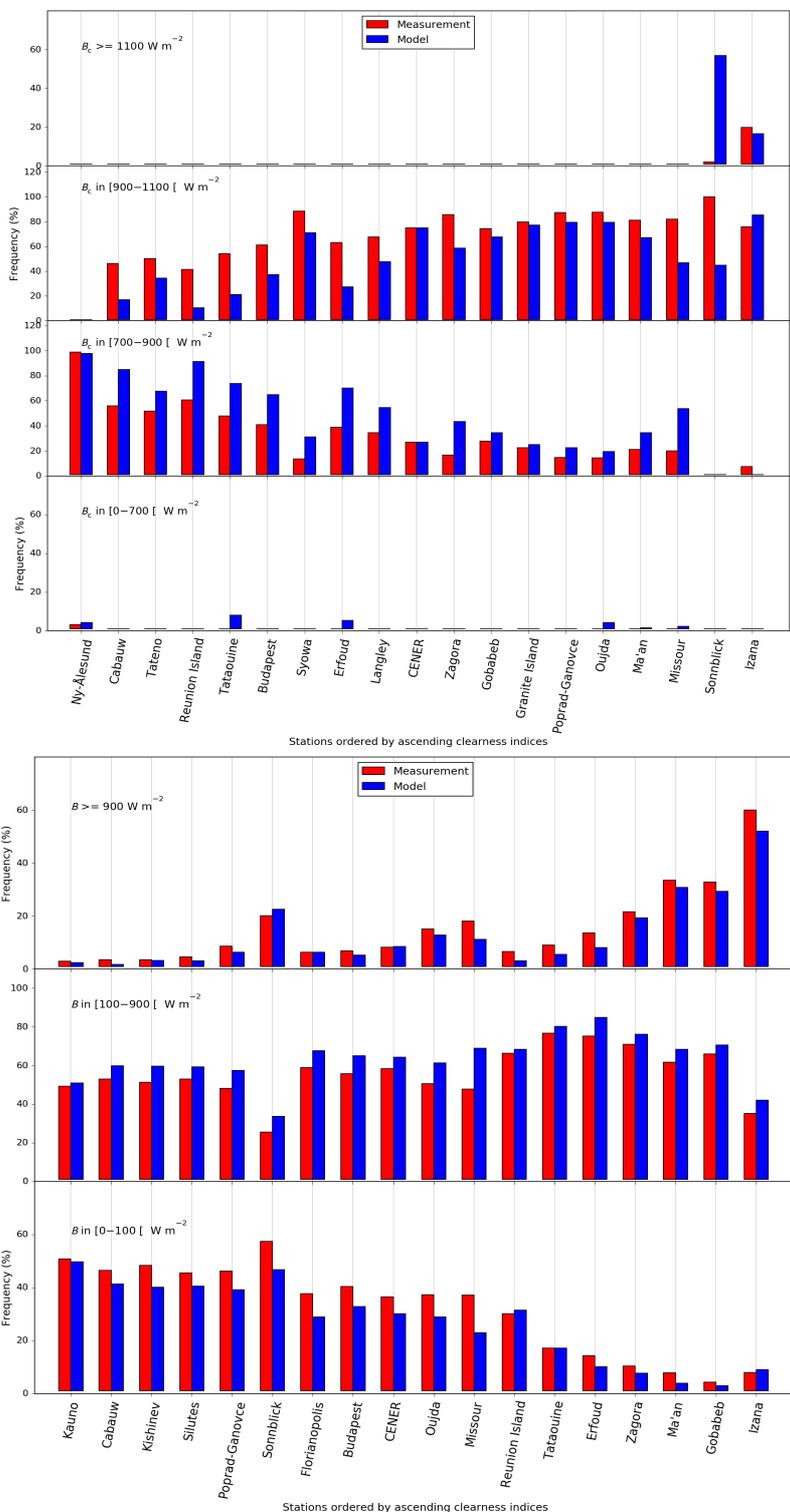


Figure 3.11. Frequency distribution of measurements for direct irradiances. Top: McClear. Bottom: CAMS-RAD.

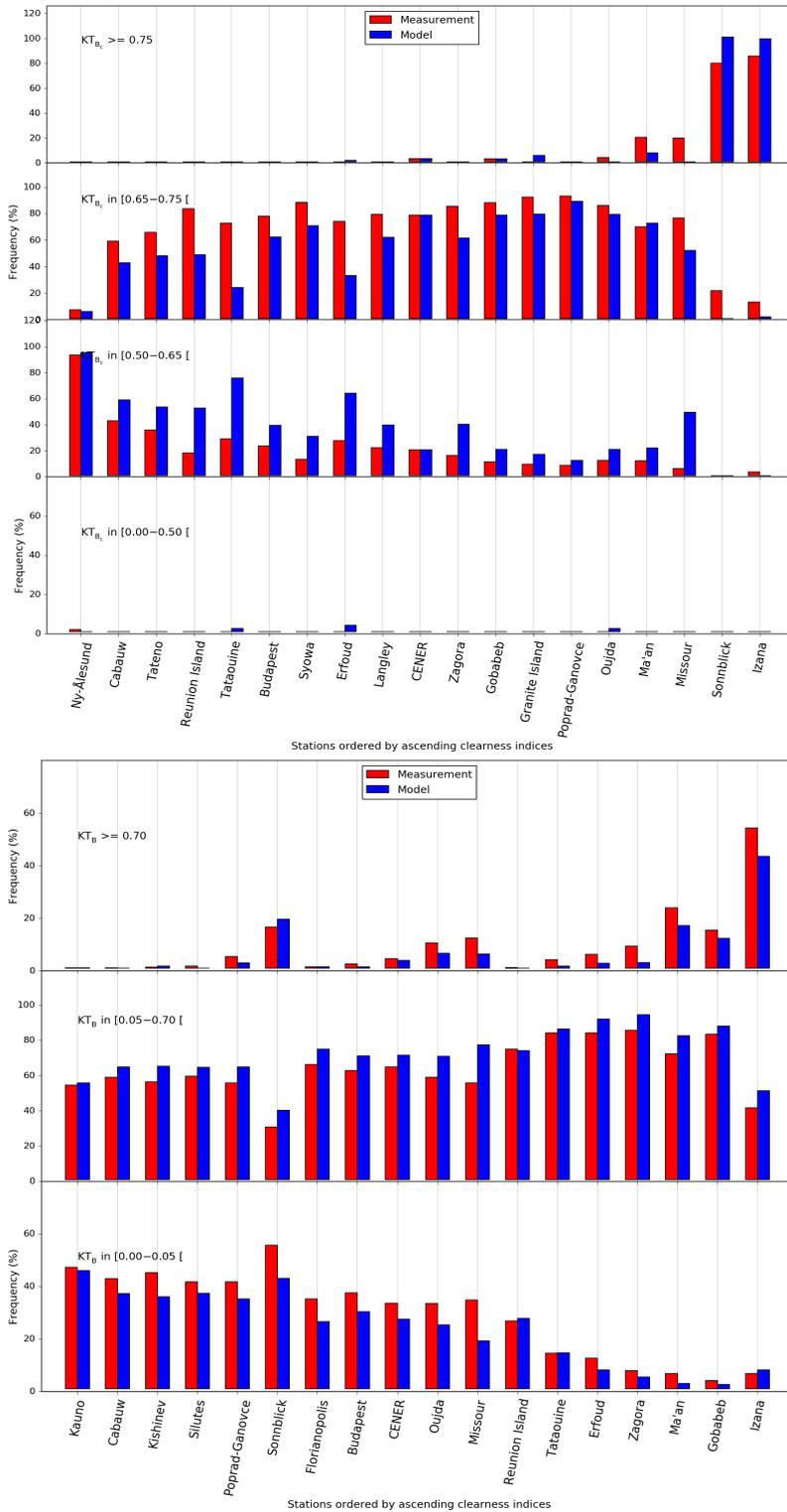


Figure 3.12. Frequency distribution of measurements for direct clearness index. Top: McClear. Bottom: CAMS-RAD.



### 3.4 Ability to reproduce the monthly means and standard deviation for the period

The final batch of analyses deals with the capability of CRS to reproduce the monthly means of the irradiance for each month of the period and its variability within a month, expressed as the standard-deviation of the hourly values (estimates and observations) within this month. Figures 3.13 to 3.15 are respectively for  $G$ ,  $D$  and  $B$ .

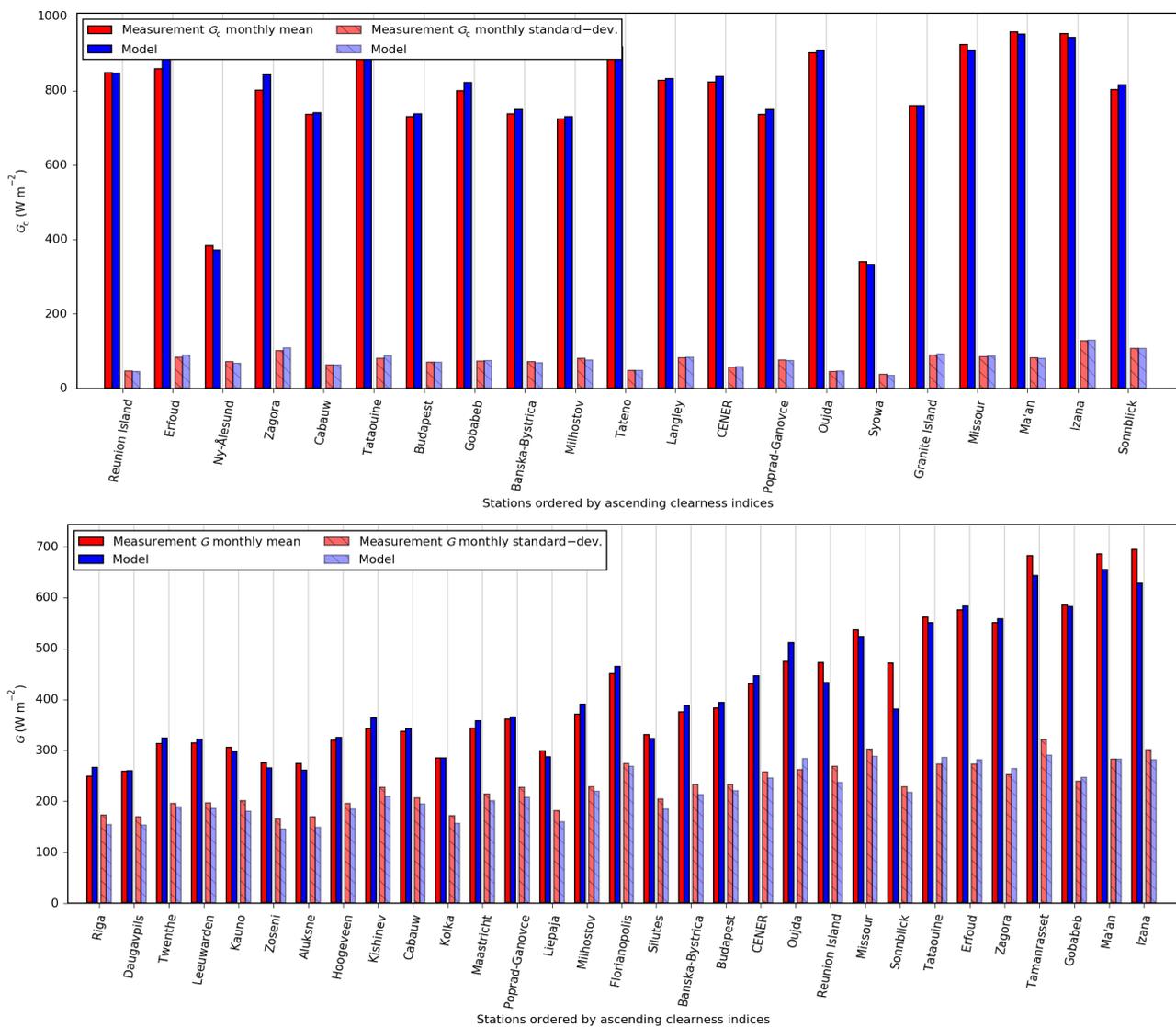


Figure 3.13. Monthly means and standard-deviations for global irradiance. Top: McCclear. Bottom: CAMS-RAD.

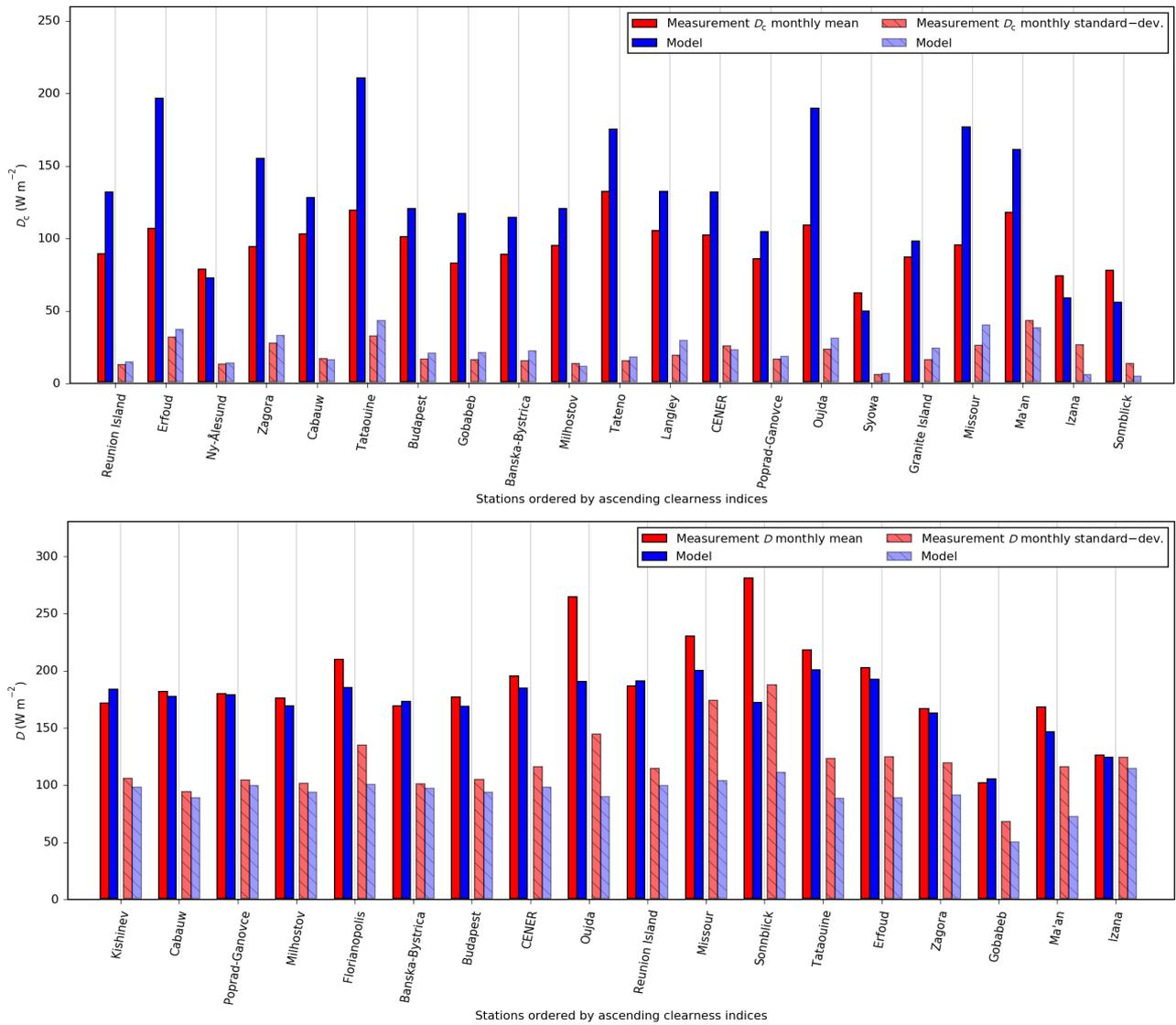


Figure 3.14. Monthly means and standard-deviations for diffuse irradiance. Top: McClear. Bottom: CAMS-RAD.

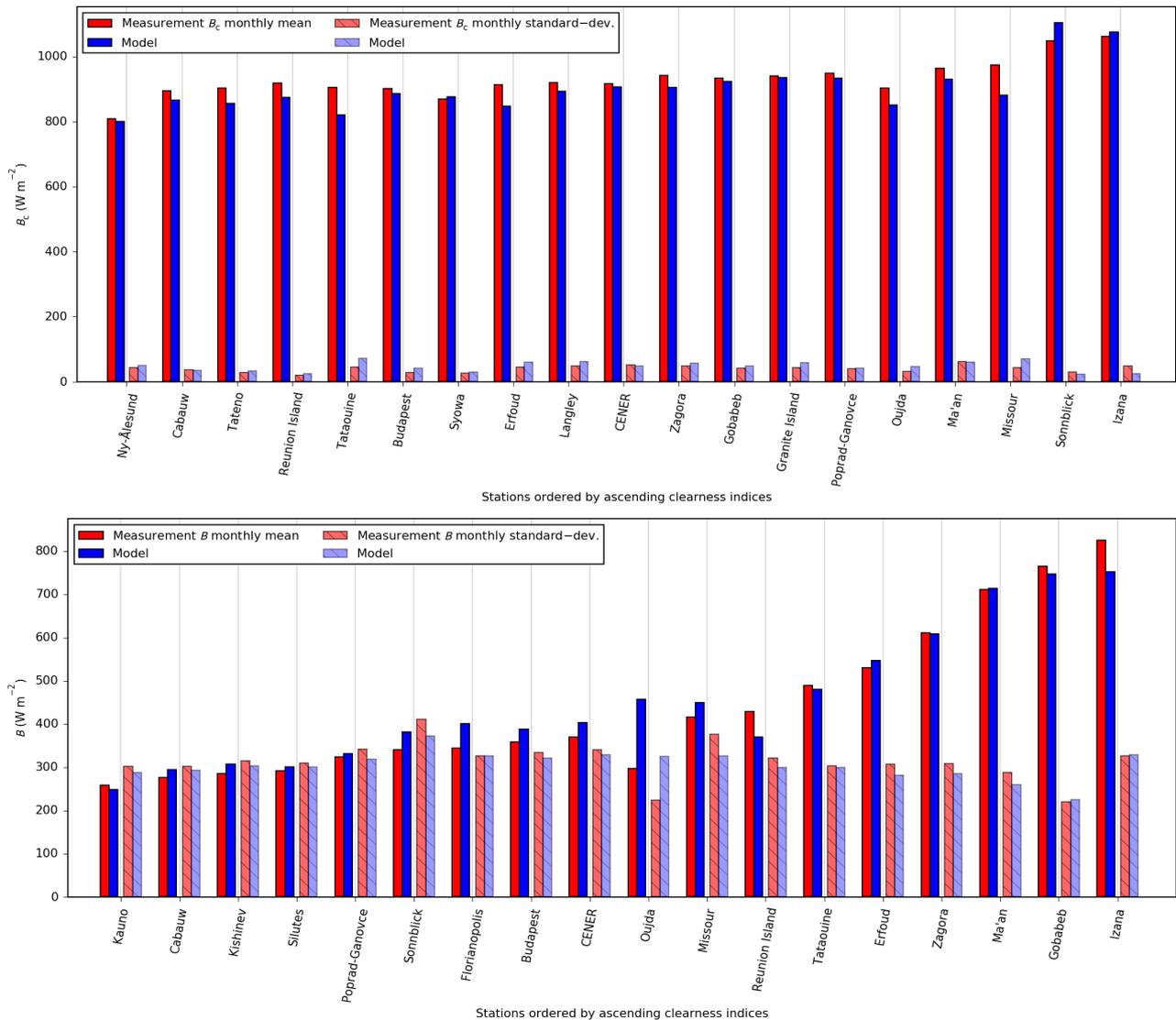


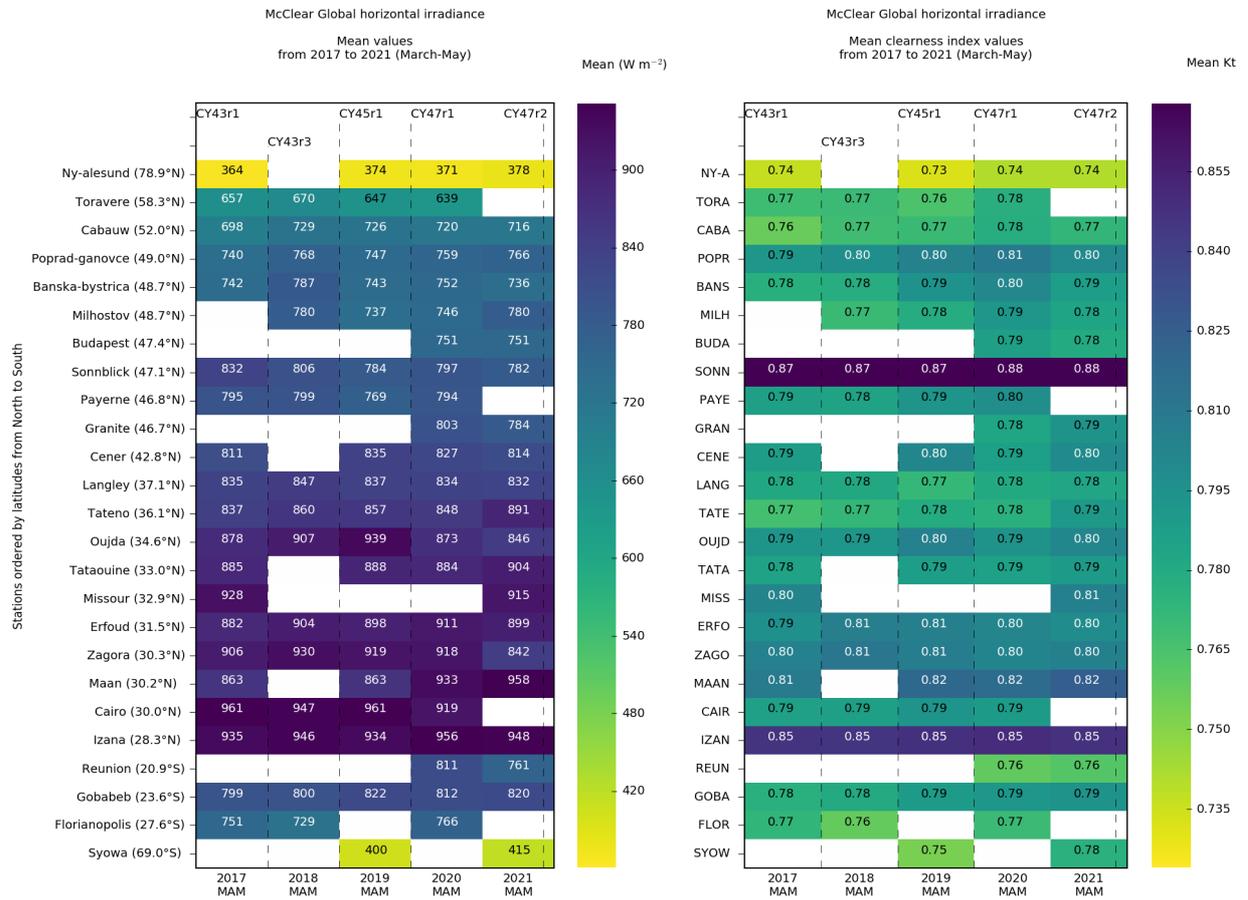
Figure 3.15. Monthly means and standard-deviation for direct normal irradiance. Top: McClear. Bottom: CAMS-RAD.

### 3.5 Multi-annual statistical indicators

Statistical indicators (mean irradiance, mean KT, relative bias and relative RMSE) have been computed for the MAM period and for the years 2017 to 2021. Figures 3.16 to 3.18 are respectively for  $G$ ,  $D$  and  $B$ .



### 3.5.1 Global irradiance



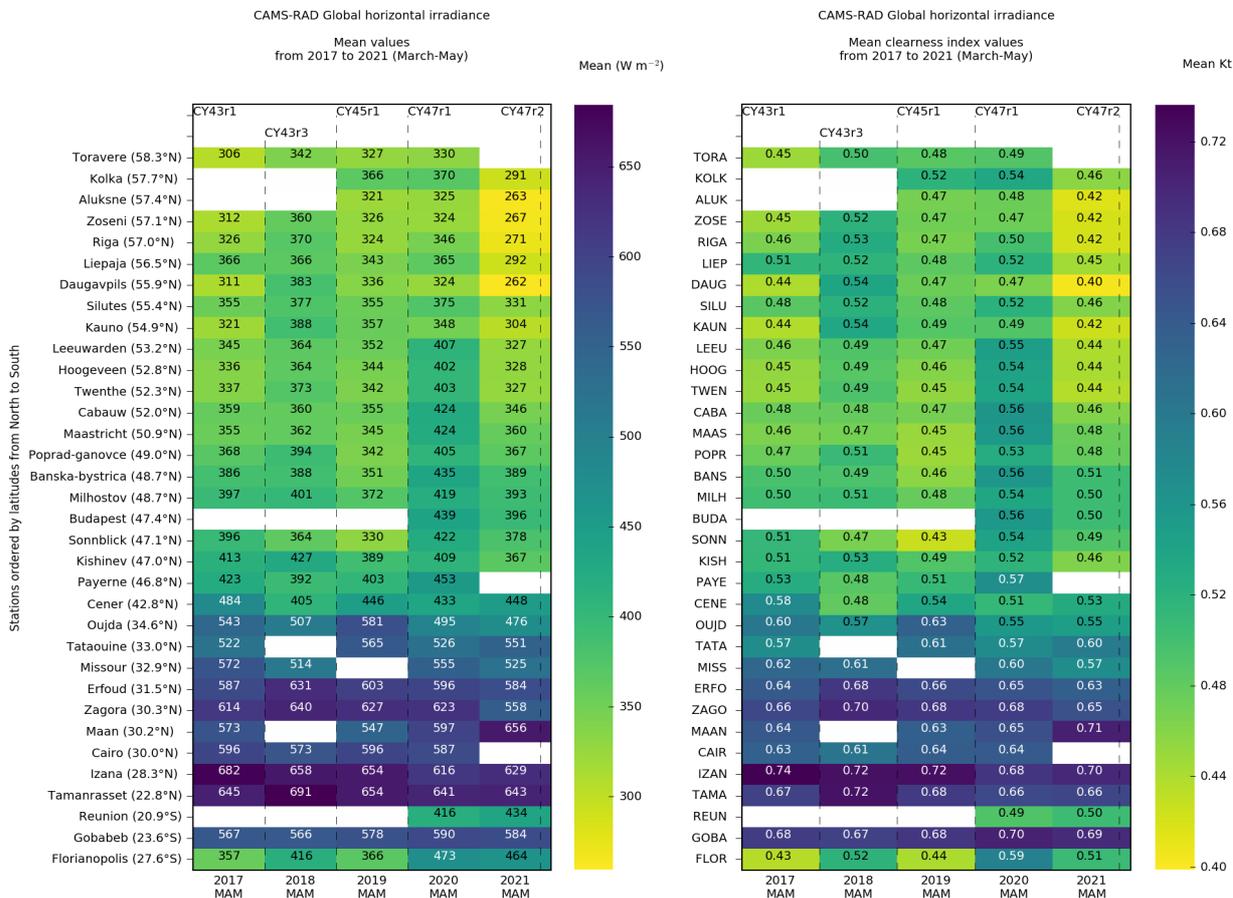
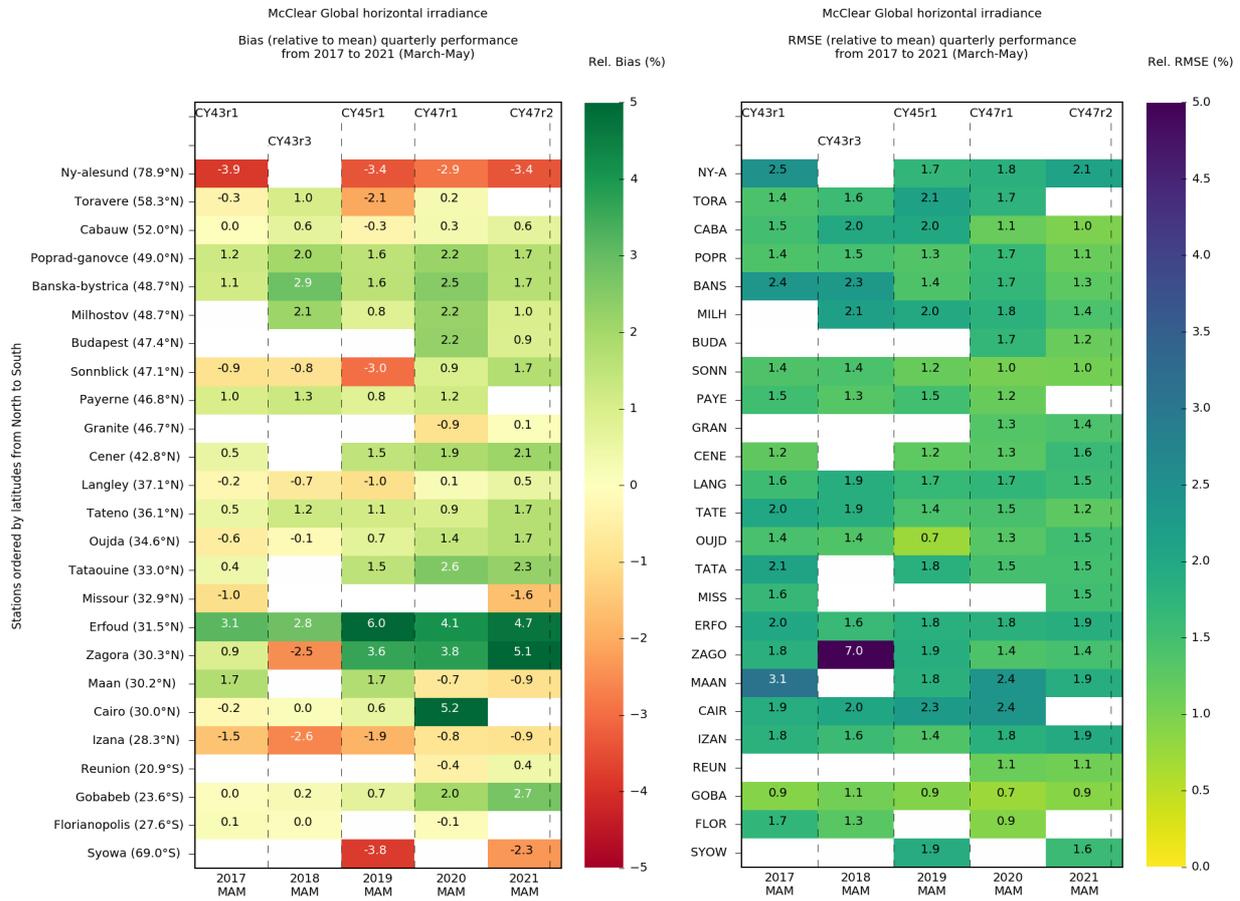


Figure 3.16a. Multi-annual means for global horizontal irradiance (left) and clearness index (right).  
Top: McClear. Bottom: CAMS-RAD.



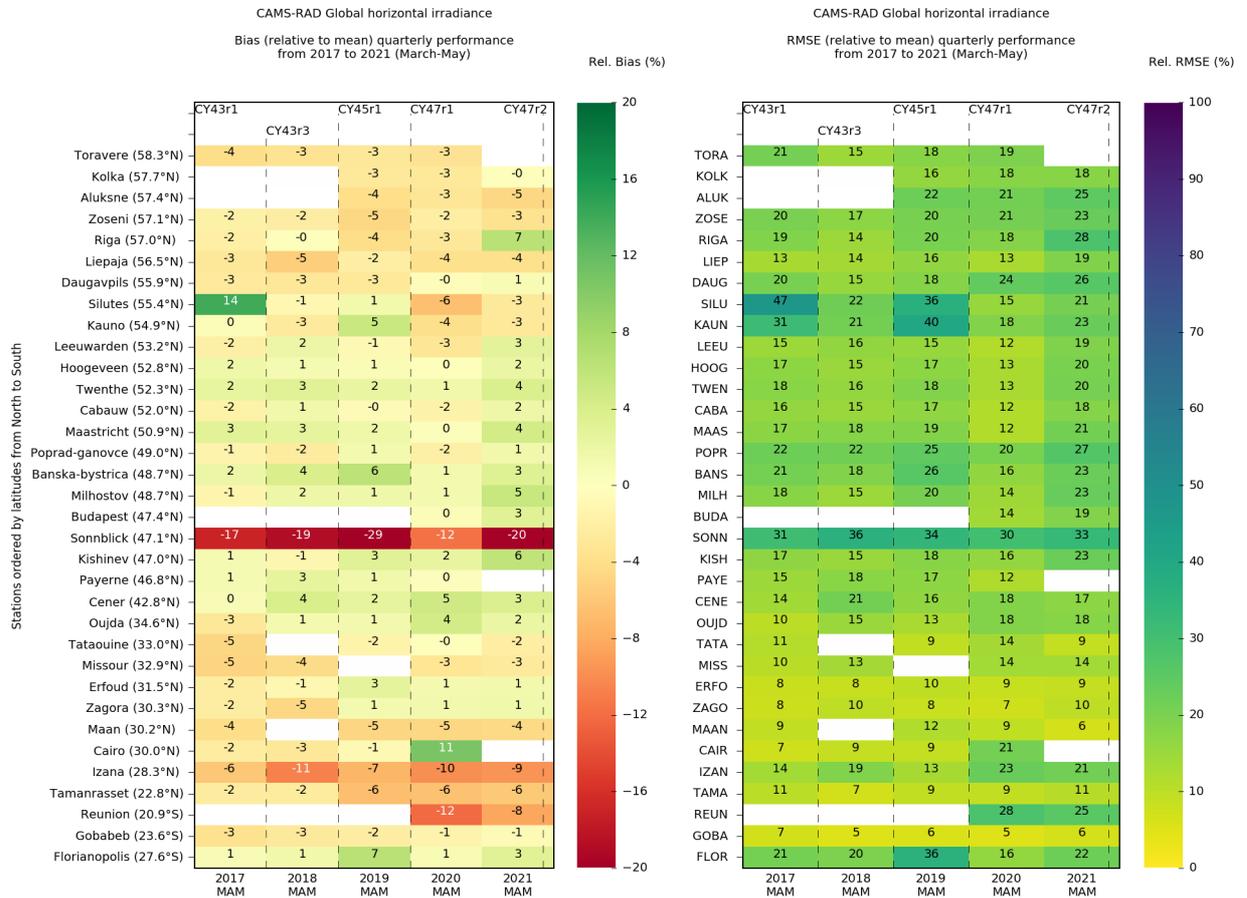
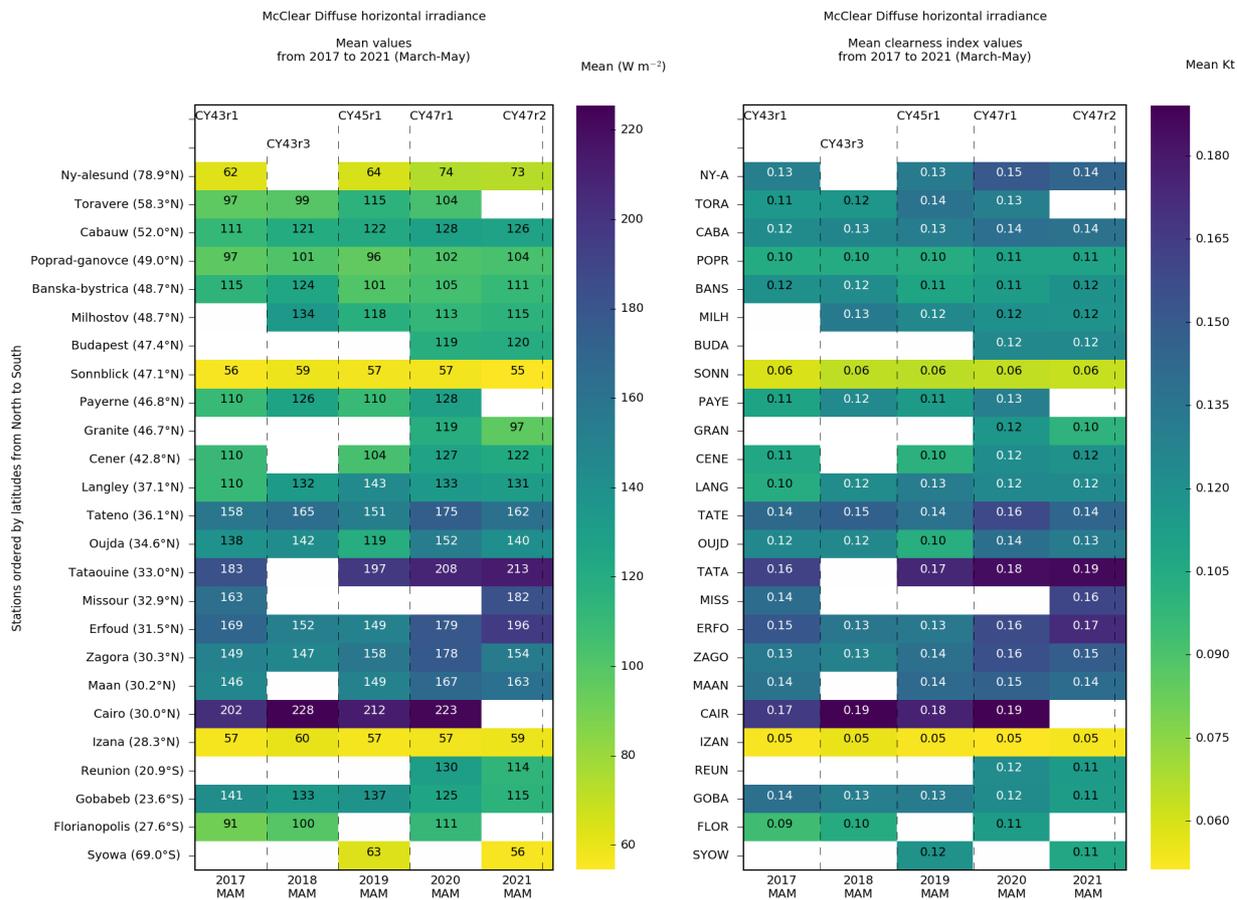


Figure 3.16b. Multi-annual global horizontal irradiance relative bias (left) and RMSE (right).  
Top: McClear. Bottom: CAMS-RAD.



### 3.5.2 Diffuse irradiance



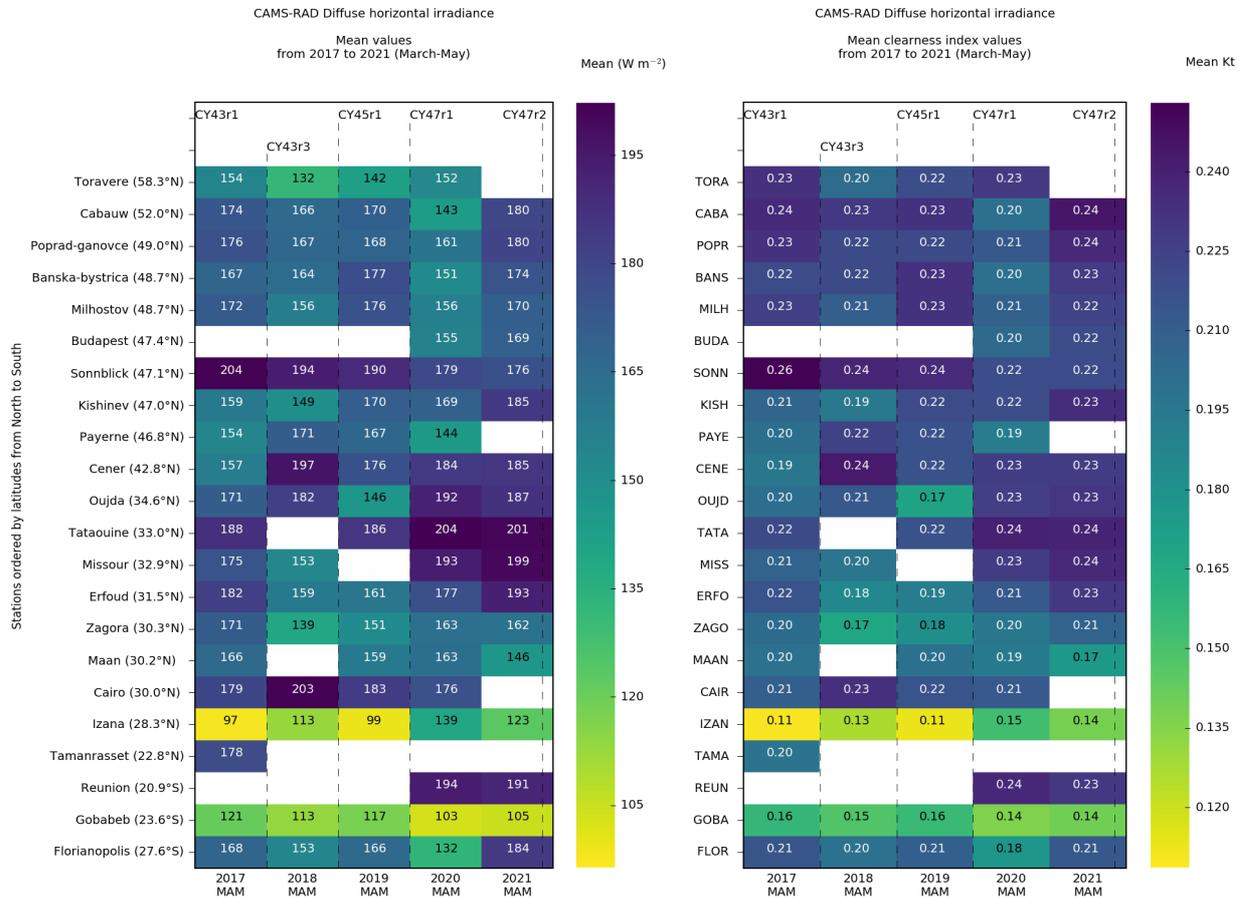
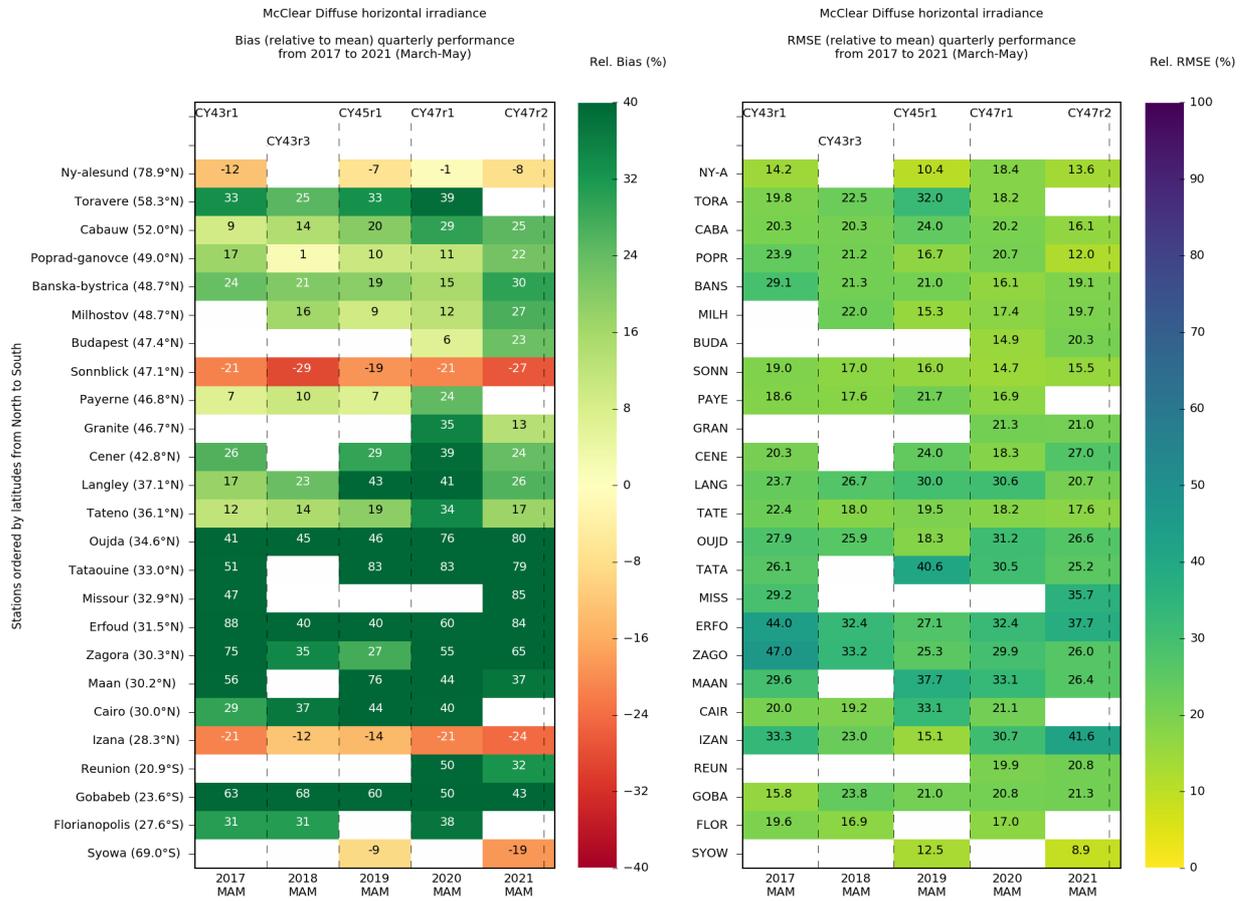


Figure 3.17a. Multi-annual means for diffuse horizontal irradiance (left) and clearness index (right). Top: McClear. Bottom: CAMS-RAD.



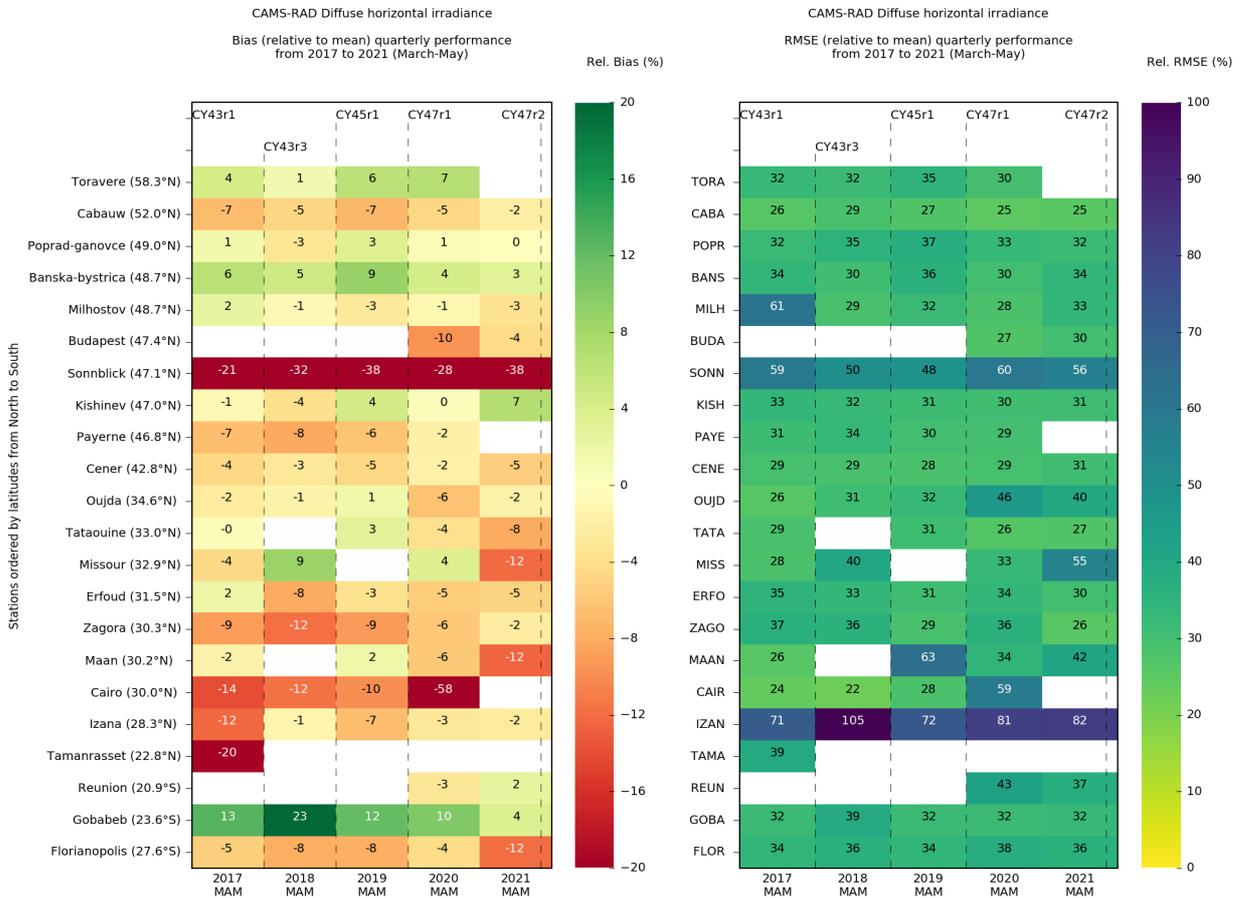
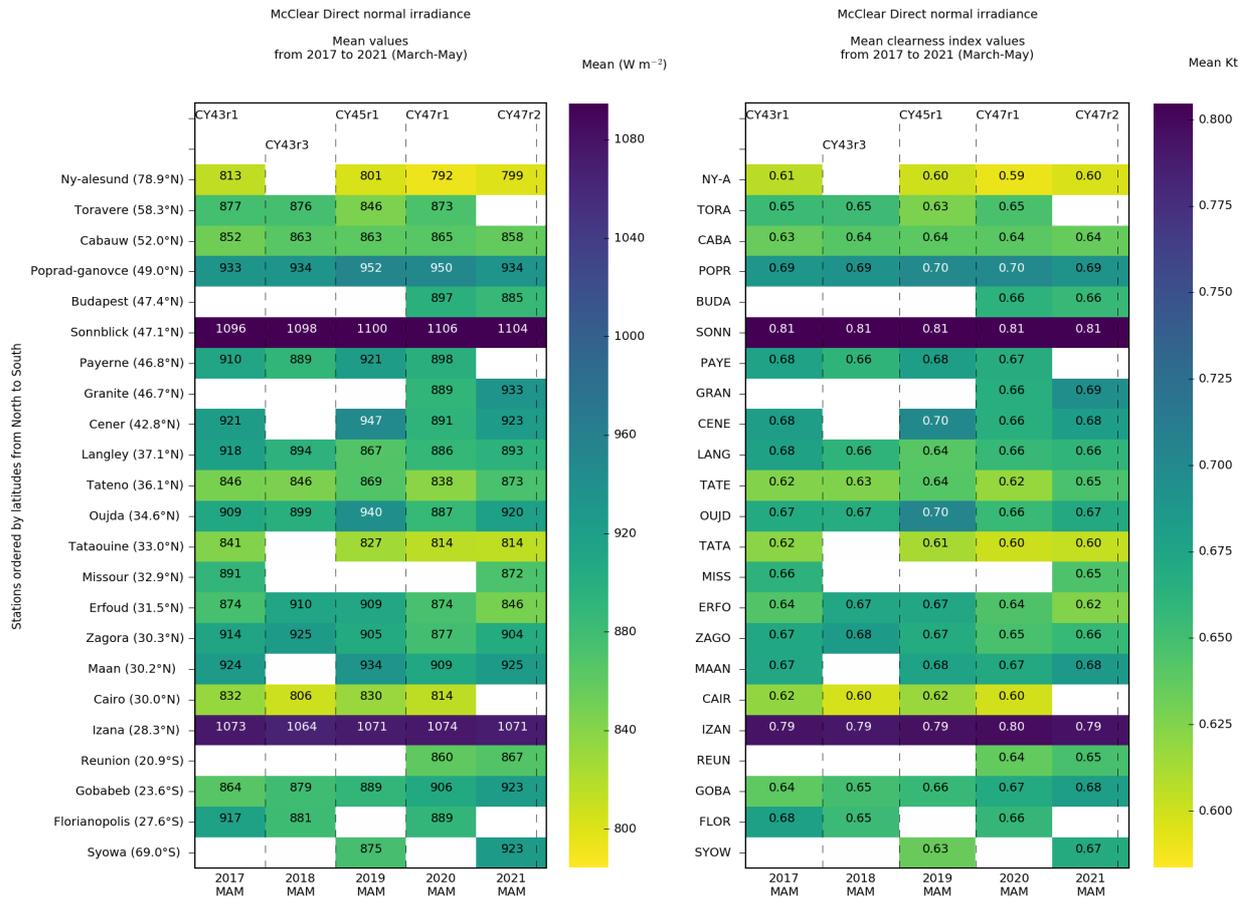


Figure 3.17b. Multi-annual diffuse horizontal relative bias (left) and RMSE (right).  
Top: McClear. Bottom: CAMS-RAD.



### 3.5.3 Direct normal irradiance



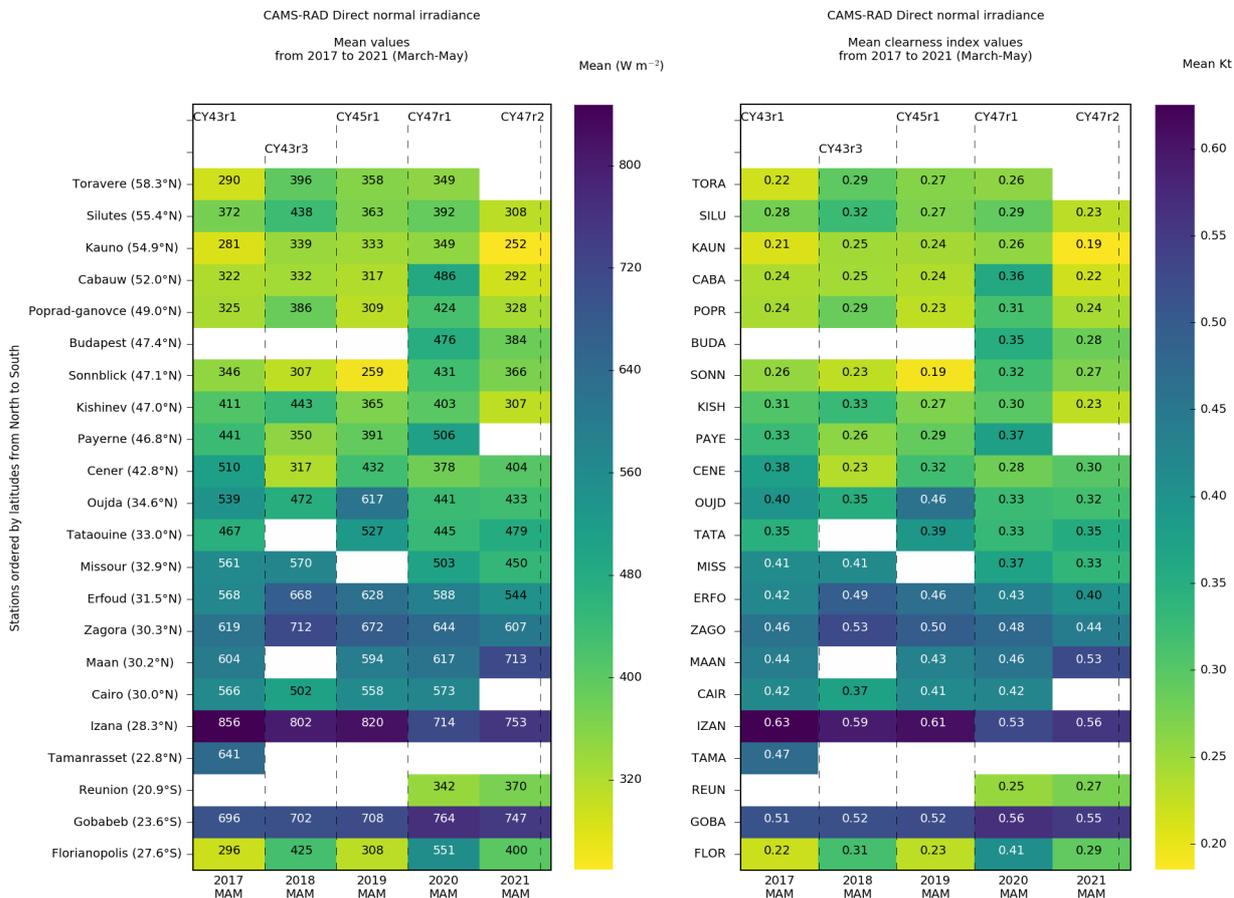
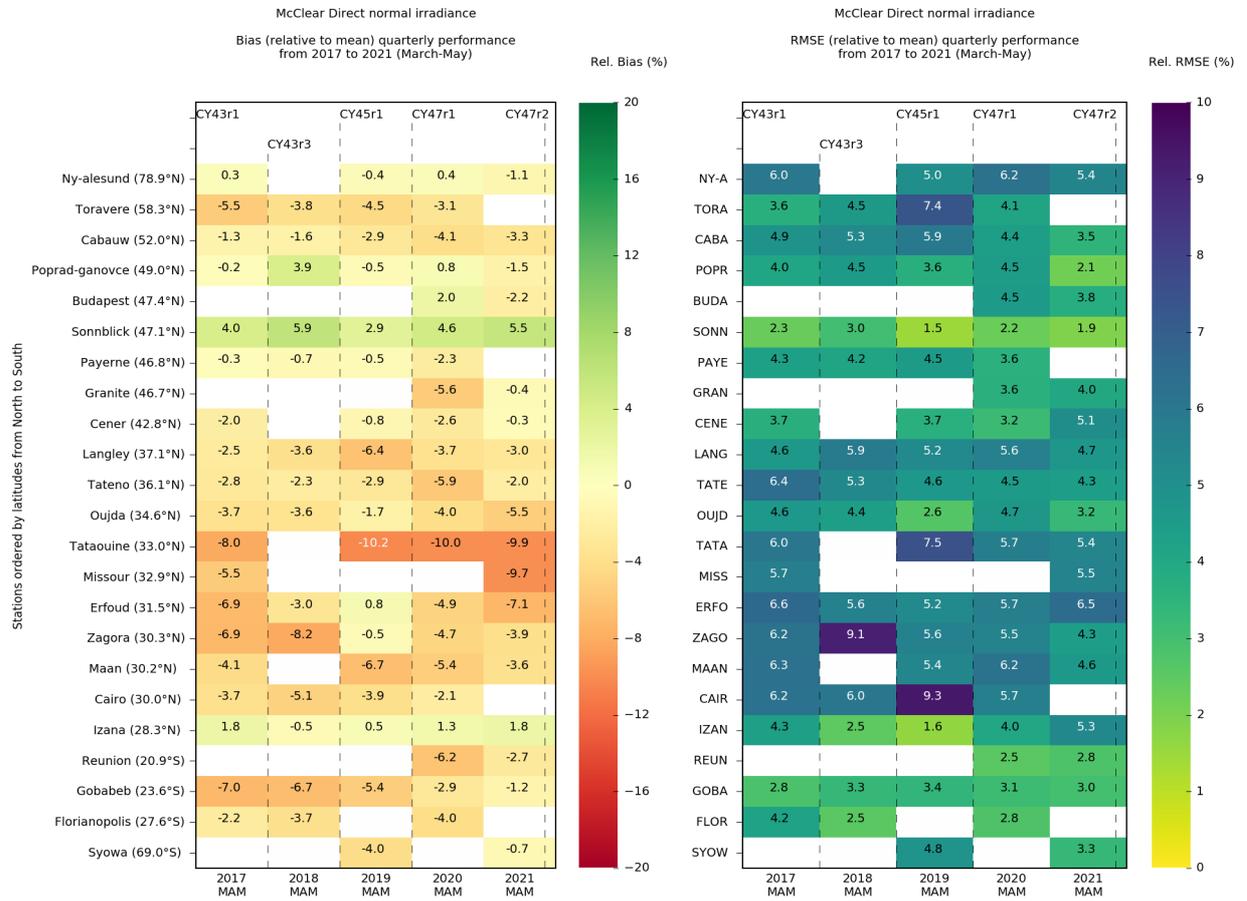


Figure 3.18a. Multi-annual means for direct normal irradiance (left) and clearness index (right).  
 Top: McClear. Bottom: CAMS-RAD.



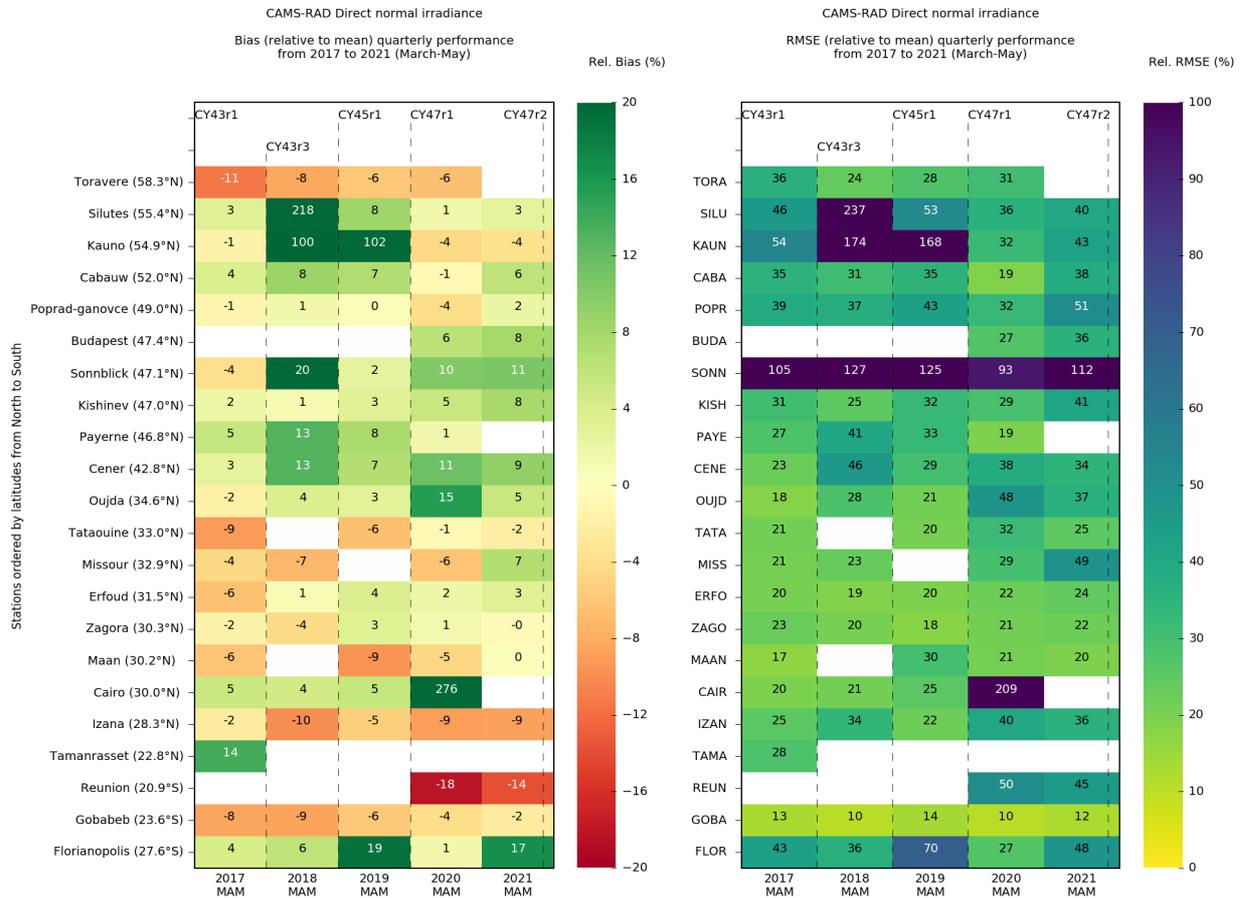


Figure 3.18b. Multi-annual direct normal irradiance relative bias (left) and RMSE (right).  
Top: McClear. Bottom: CAMS-RAD.

### 3.6 Recommendations

As already reported in previous reports, there is room to improve the CRS for large solar zenith angles. There are several cases with large *B* values observed in the ground observations which are underestimated in CRS. The cloud analysis from Meteosat images indicates a fully cloudy pixel with cloud coverage of 100 % and a low cloud optical depth. In the previous used scheme for CRS v3.2 the cloud optical depth was set to a clipping value of 0.5 even if the retrieval provides a smaller value. This was a meaningful setting for the original application field of the used cloud retrieval package, but is not appropriate for surface radiation calculations. The exact value of the cloud optical depth plays a greater role when the sun is low above horizon which happens very often in winter at great latitude, and at the beginning and end of the day in any case. This clipping value has been removed in the current version of the cloud retrieval package and therefore in CRS v4.0.



The CRS is composed of two models (see <https://atmosphere.copernicus.eu/solar-radiation> and the User Guide published there). The sky model of the CRS - called McClear - exploits the CAMS service information on aerosol properties and total column content in water vapour and ozone. It provides irradiances that would be observed in cloud-free conditions. McClear generally performs well as shown by several publications (Eissa et al., 2015; Lefèvre et al., 2013, Lefèvre, Wald, 2016; Marchand et al., 2017). However, detailed analyses of the deviations for CRS reveal discrepancies that may be large also for cloud-free cases. These discrepancies may be traced back to the over- or underestimation of the occurrences of cloud-free cases or to any gross errors in aerosol conditions modelled as input to McClear. Note should be taken that there is no means in this study to discriminate the cases of underestimation of the occurrences of overcast cases and those of underestimation of the optical depth. Both cases appear as an underestimation by CRS of the frequency of low clearness indices. Similarly, there is no means to discriminate the cases of overestimation of the occurrences of medium skies cases and those of underestimation of the optical depth of the optically thick clouds or overestimation of the optical depth of the optically thin clouds. These cases appear as an overestimation by CRS of the frequency of medium clearness indices. Finally, there is no means to discriminate the cases of underestimation of the occurrences of cloud-free cases and those of overestimation of the optical depth of the optically thin clouds. These cases appear as an underestimation by CRS of the frequency of large clearness indices.

## 4 Sources of data

Measurements are taken from various sources and measuring stations that are discussed in this section. Note that a more detailed presentation is done in the ground measurement catalogue updated every year which is accessible via the CAMS help desk:

CAMS2\_73\_2021SC1-D1.4.1-2021Q4\_ground\_catalogue\_202112\_v2.pdf for December 2021

### 4.1 Sources of data

Efforts are made to build the quarterly validation reports with the same set of stations to better follow and monitor the quality of the irradiance products delivered by the CRS, though this is difficult as discussed later.

Measurements originate from different networks as reported in Table 4.1. They have been acquired in different time systems (UT: Universal Time, TST: True Solar Time, GMT: Greenwich Meridian Time). No change in time system is performed during this validation. The handling of the different time systems is described in the annex A describing the procedure for validation.

Table 4.1. Source of data for each station, time system and type of data (*G*, *B*, *D* stands respectively for global, direct at normal incidence and diffuse).



Station	Source of data	Time system	Initial time integration interval	Type of data acquired
Aluksne	Latvian Environment, Geology and Meteorology Centre (LEGMC)	TST	1 h	G - -
Kolka				G - -
Dobele				G B -
Riga				G - -
Zoseni				G - -
Liepaja				G - -
Rucava				G - -
Daugavpils				G - -
Silutes	Lithuanian Hydrometeorological Service (LHMS)	UT	1 h	G B -
Kauno				
Leeuwarden	KNMI	UT	1 h	G - -
Hoogeveen				
Twenthe				
Maastricht				
Poprad-Ganovce	Slovak Hydrometeorological Institute (SHMI)	UT	1 min	G B D
Banska-Bystrica				G - D
Milhostov				G - D
Kishinev	WRDC	GMT+2	1 h	G B D
Oujda	EnerMENA	UT	1 min	G B D
Tataouine		UT+1		
Fki Ben Salah		UT		
Missour		UT		
Erfoud		UT		
Cairo		UT+2		
Zagora		UT		
Ma'an		UT+2		
Ny-Ålesund	BSRN	UT	1 min	G B D
Toravere				
Cabauw				
Budapest				
Sonnblick				
Payerne				
Granite Island				
CENER				
Langley				
Tateno				
Izaña				
Tamanrasset				
Reunion island				
Gobabeb				
Florianopolis				
Syowa				



## 4.2 Short description of the stations selected for the validation

The geographical coordinates of the selected stations (see maps in [Figure 2.1](#)) are given in Table 4.2.

Table 4.2. List of stations used to realize the validation report in general, and their coordinates, ordered from North to South.

Country	Station	Latitude	Longitude	Elevation a.s.l. (m)
Norway (Spitzbergen)	Ny-Ålesund	78.925	11.930	11
Estonia	Toravere	58.254	26.462	70
Latvia	Aluksne	57.440	27.035	197
Latvia	Kolka	57.743	22.584	30
Latvia	Zoseni	57.135	25.906	188
Latvia	Riga	56.951	24.116	6
Latvia	Dobele	56.620	23.320	42
Latvia	Liepaja	56.475	21.021	4
Latvia	Rucava	56.162	21.173	19
Latvia	Daugavpils	55.870	26.617	98
Lithuania	Silutes	55.352	21.447	5
Lithuania	Kauno	54.884	23.836	77
The Netherlands	Hoorn	53.393	5.346	0
The Netherlands	Leeuwarden	53.225	5.755	1
The Netherlands	Hoogeveen	52.750	6.575	16
The Netherlands	Twenthe	52.273	6.897	34
The Netherlands	Cabauw	51.972	4.927	-1
The Netherlands	Vlissingen	51.442	3.596	8
The Netherlands	Maastricht	50.906	5.762	114
United Kingdom	Camborne	50.217	-5.317	88
Slovakia	Poprad-Ganovce	49.035	20.324	709
Slovakia	Banska-Bystrica	48.734	19.117	427
Slovakia	Milhostov	48.663	21.722	105
Hungary	Budapest	47.429	19.182	139
Austria	Sonnblick	47.054	12.958	3109
Moldova	Kishinev	47.000	28.817	205
Switzerland	Payerne	46.815	9.944	491
United States	Granite Island	46.721	-87.411	208
France	Carpentras	44.083	5.059	100
Spain	CENER	42.816	-1.601	471
United States	Langley	37.104	-76.387	3



Country	Station	Latitude	Longitude	Elevation a.s.l. (m)
Spain	PSA	37.091	-2.358	500
Japan	Tateno	36.058	140.126	25
Morocco	Oujda	34.650	-1.900	617
Morocco	Missour	32.860	-4.107	1107
Morocco	Fki Ben Salah	32.578	-6.622	485
Morocco	Erfoud	31.491	-4.218	859
Morocco	Zagora	30.272	-5.852	783
Egypt	Cairo	31.036	31.009	104
Tunisia	Tataouine	32.974	10.485	210
Jordan	Ma'an	30.172	35.818	1012
Spain	Izaña	28.309	-16.499	2373
Algeria	Adrar	27.878	-0.270	262
Algeria	Tamanrasset	22.790	5.529	1385
France	Reunion island	-20.9014	55.4836	116
Namibia	Gobabeb	-23.561	15.042	407
Brazil	Florianopolis	-27.605	-48.523	11
Antarctica (Cosmonaut Sea)	Syowa	-69.005	39.589	18

The selected stations are located in several different climates as reported in Table 4.3. The description of climates is taken from the updated world map of the Köppen-Geiger climate classification by Peel et al. (2007).



Table 4.3. List of climates and corresponding stations

Climate	Stations
<b>As:</b> Tropical savanna climate, dry summer	Reunion island
<b>BWh:</b> Arid and hot climate of desert type	Tataouine, Erfoud, Cairo, Zagora, Ma'an, Tamanrasset, Fki Ben Salah
<b>BWk:</b> Arid and cold climate of desert type	Gobabeb
<b>Cfa:</b> Temperate climate without dry season and hot summer	Florianopolis, Tateno
<b>Cfb:</b> Temperate climate without dry season and warm summer	Hoorn, Hoogeveen, Twenthe, Cabauw, Leeuwarden, Maastricht, Vlissingen, Camborne, Payerne, CENER
<b>Csa:</b> Temperate climate with dry and hot summer	Oujda, Missouri
<b>Csb:</b> Temperate climate with dry and warm summer (Mediterranean climate)	Carpentras, PSA, Izaña, Langley
<b>Dfa:</b> Continental wet. Cold climate without dry season and hot summer	Poprad-Ganovce, Banska-Bystrica, Milhostov
<b>Dfb:</b> Continental wet. Cold climate without dry season and warm summer	Toravere, Zoseni, Riga, Dobeles, Daugavpils, Liepaja, Aluksne, Kolka, Rucava, Silutes, Kauno, Kishinev, Budapest, Granite Island
<b>Dfc:</b> Subarctic climate	Sonnblick
<b>ET:</b> Polar tundra climate with no true summer	Ny-Ålesund
<b>EF:</b> Ice cap climate	Syowa

Among the set of stations, are several stations, such as Toravere, which are at the edge of the field of view of the Meteosat Second Generation satellites and most likely at the edge of physical assumptions used when retrieving cloud properties. This validation is meant to include extreme cases into the station list.

One may note that though the validation aims at validating the variables  $G$ ,  $B$ , and  $D$  delivered by the CRS, several stations are included that measure only the global irradiance  $G$ . They have been selected in order to check the spatial consistency of the quality of the CRS products within the same network and same climate. [Figure 2.1](#) shows several groups of stations that are close to each other within the same climate: The Eastern Baltic area, The Netherlands, and Slovakia. One expects similar performances of CRS within a group.

It should be underlined that the validation process cannot be automated in its present form. Hence, the number of selected stations and the choice of these stations is a trade-off between the desire to cover as much as possible various climatic conditions and the amount of human resources available.



### 4.3 Evolution of the list of stations

The selection of the stations considers the results published in scientific journals or conferences. Several authors have compared McClear or CRS estimates to ground-based measurements. These publications are analysed to see if there are differences in quality when compared to our own validations.

The conclusions of these analyses may have an impact on the choice and the number of stations selected for the quarterly validation. For example, if one or more authors report performances that are dissimilar to ours in geographical areas for which we do not have stations, we will try our best to obtain measurements from stations if they follow our constraints in quality and timely access. In another example, authors may have made in-depth studies of the performances of CRS in geographical areas where we have stations, such as the Netherlands where we are using several KNMI stations. Given this background, exploiting a single KNMI station may be sufficient now to monitor the performances of CRS in this area.

### 4.4 Stations under evaluation

Some stations providing unusual observations are commented below.

From the #28 issue, some issues are not commented anymore. It concerns (see last #27 issue for details):

- The KNMI station of Hoorn was removed from the set used for the quarterly validation. This station will be reported in the next ground data catalogue for information and as a warning to users at the coastal limit.
- The enerMENA station of Missouri which gave abnormal overestimated measurements of diffuse irradiances during April and June 2018. This station was under maintenance since then and resume on October 2019.

From the #31 issue, some other stations are not commented anymore (see last #30 issue for details):

- The Lithuanian stations of Silutes and Kauno. Thanks to the renovation operated in January 2020, problems have been solved, included many times shifts.

Still under evaluation are stations Fki Ben Salah, Zagora, Erfoud and Oujda in Morocco, Cairo in Egypt. Some discrepancies between estimated CRS and measurements have been reported in previous reports.

In the #32 issue, the BSRN station of Florianopolis was illustrated regarding its bad results for the SON 2020 quarter.

From #33 issue, all the figures have been updated with the version 4.0 of the CRS.



### 4.4.1 Cairo (Egypt)

During the past 2019 and 2020 quarters some bad values for the *D* and *B* components appeared at Cairo which were not eliminated with the quality check process. Contrary to the global irradiance, the diffuse and direct irradiances present very large variations in Feb.-June 2020 (Fig. 4.1). A tracker failure along with a lack of cleaning during failure period explain these anomalies which disappear by mid-June before a new tracking failure in October. According to the provider *D* and *B* are not recommended for the validation.

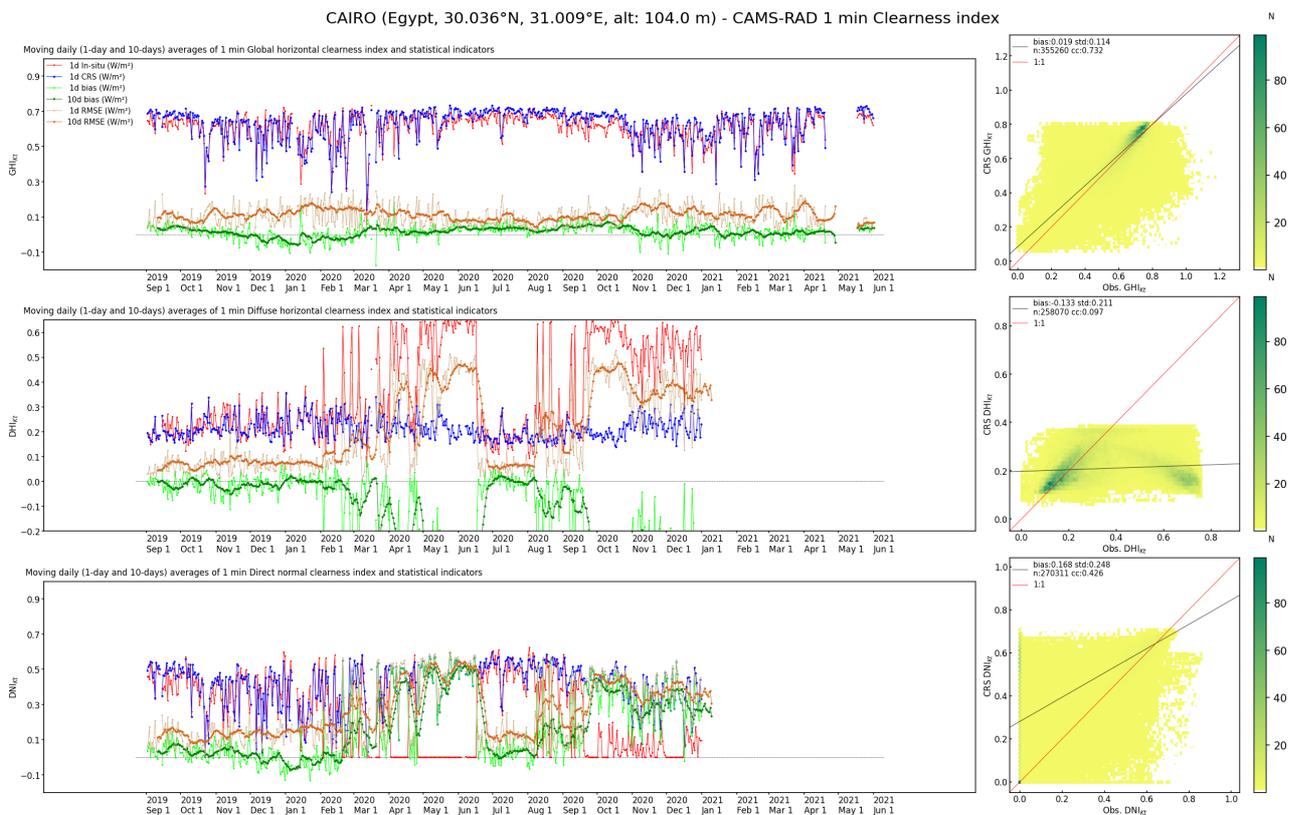


Figure 4.1. Station Cairo, daily and 10 days running average of clearness index from Sept. 2019 to May 2021.

Top: Global. Middle: Diffuse. Bottom: Direct normal clearness index.



### 4.4.2 Zagora (Morocco)

The RSI sensor has been exchanged in January 2020. A new calibration has been applied that corrects the  $G$  component discrepancy between measured and estimated that was observed before. Nevertheless,  $B$  which is calculated from  $G$  and  $D$ , presents since then and until mid-June 2020 a discrepancy with estimated CRS that was not observed before. This discrepancy re-appears since October (Fig. 4.2).

Although some discrepancies appear during March 2021 (data eliminated in April and May) for the  $D$  and  $B$  components, no problem was reported regarding the maintenance of in-situ sensors. Thus, the data have not been eliminated from the dataset.

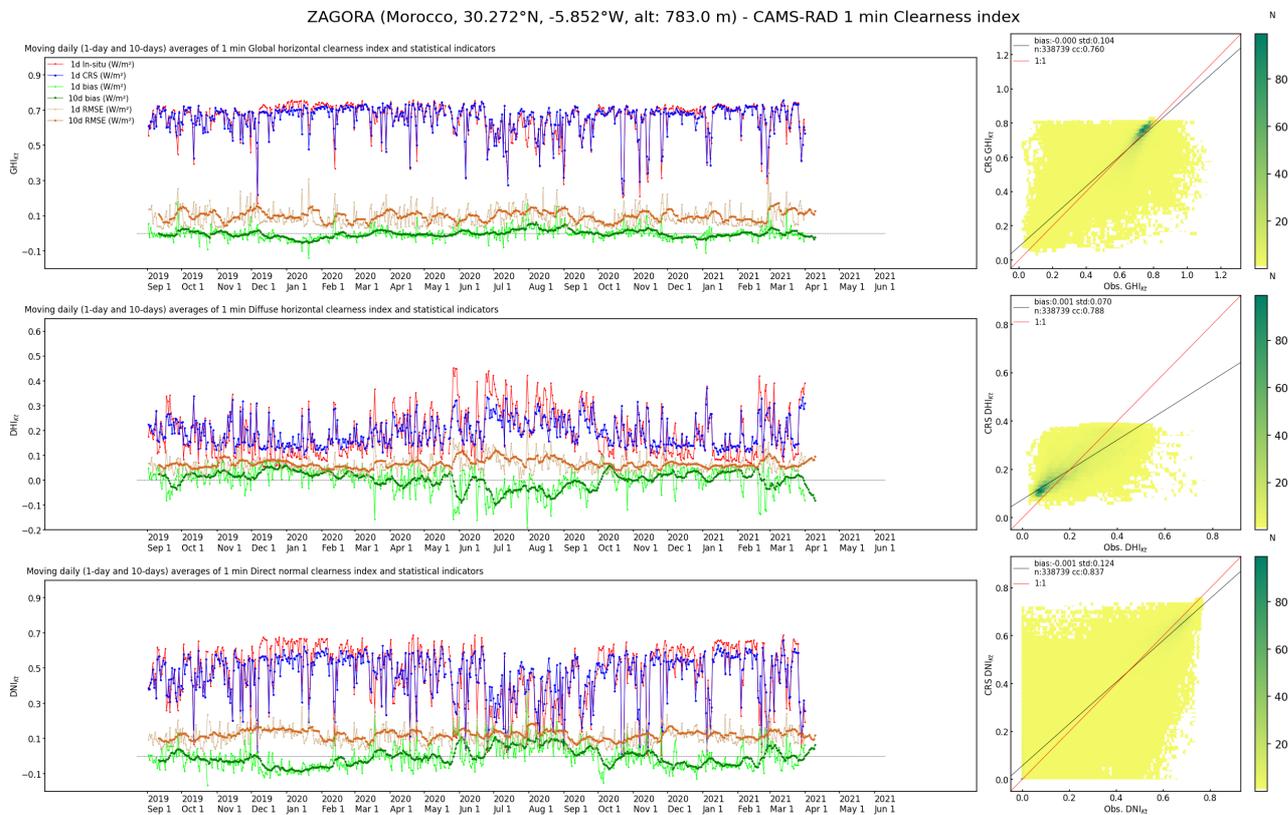


Figure 4.2. Station Zagora, daily and 10 days running average of clearness index from Sept. 2019 to May 2021.

Top: Global. Middle: Diffuse. Bottom: Direct normal clearness index.



### 4.4.3 Erfoud (Morocco)

The station Erfoud presents a decrease of  $D$  measurements from October 2019 to March 2020 and a sudden increase since then, with a concomitant variation of  $B$  in opposite way (Fig. 4.3). In this case of Erfoud, a remote site without regular cleaning, the continuously increasing deviations have been caused by dirt on the RSI sensor. Nevertheless, like Zagora, the discrepancies on  $D$  and  $B$  re-appear in October 2020 and remain until Feb. 2021 period, but disappear since then.

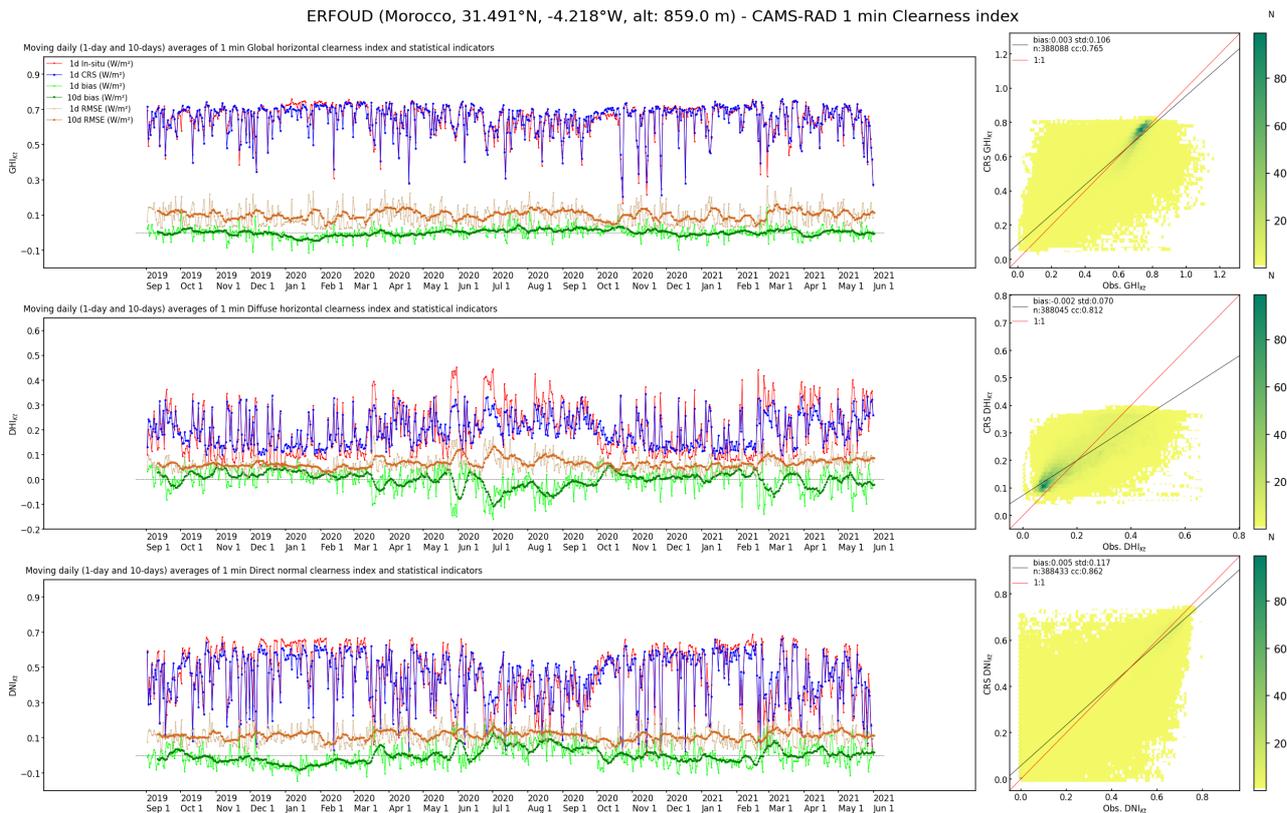


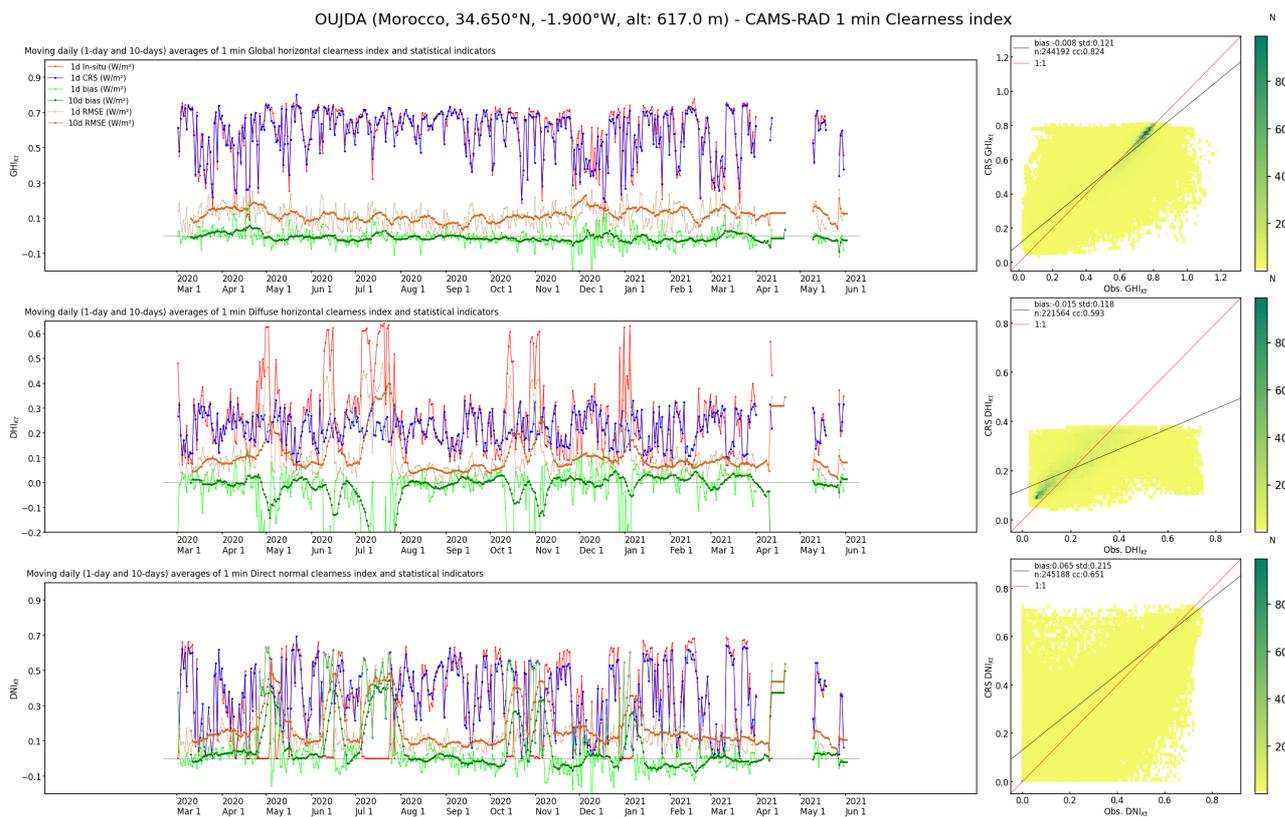
Figure 4.3. Station Erfoud, daily and 10 days running average of clearness index from Sept. 2019 to May 2021.

Top: Global. Middle: Diffuse. Bottom: Direct normal clearness index.



### 4.4.4 Oujda (Morocco)

Sensors were not cleaned during COVID-19 from March to May 2020, and a tracker failure occurred between 24 April and 3 May, and between 8-16 June which probably causes the discrepancy observed on the *D* component. No problem of maintenance was reported for March 2021, but tracker outages in April and May 2021.





### 4.4.5 Fki Ben Salah (Morocco)

During 2020 pyrhelimeter is sometimes misaligned in the afternoon due to erroneous mounting. This may explain the anomalies observed on fig. 4.5. Although misalignment still remains in 2021, the discrepancies tend to disappear.

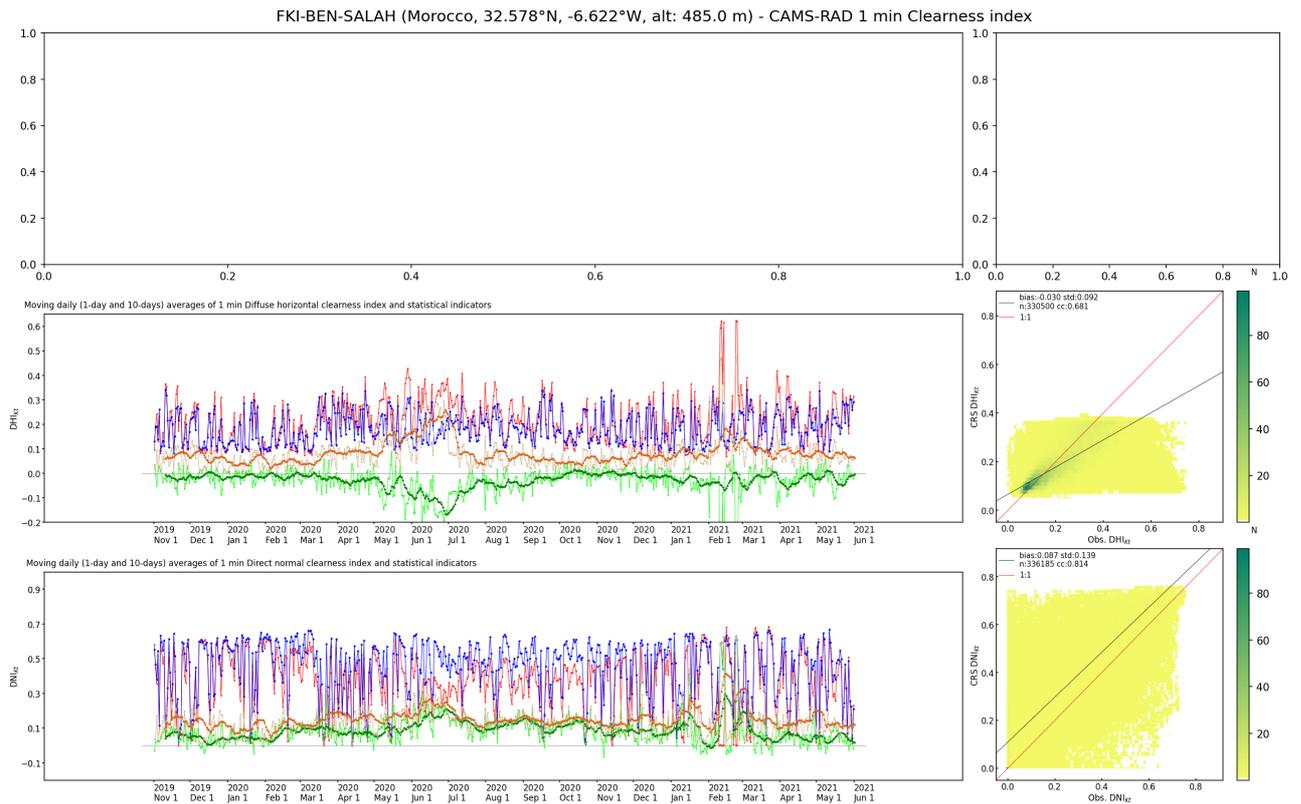


Figure 4.5. Station Fki Ben Salah, daily and 10 days running average of clearness index From Nov. 2019 to May 2021.

Top: Global. Middle: Diffuse. Bottom: Direct normal clearness index.



### 4.4.6 Florianopolis (Brazil)

The BSRN station of Florianopolis exhibits unusual and large discrepancies during Sept. 2020 for the *D* and *B* components (Fig. 4.6). This is not observed since Oct. 2020.

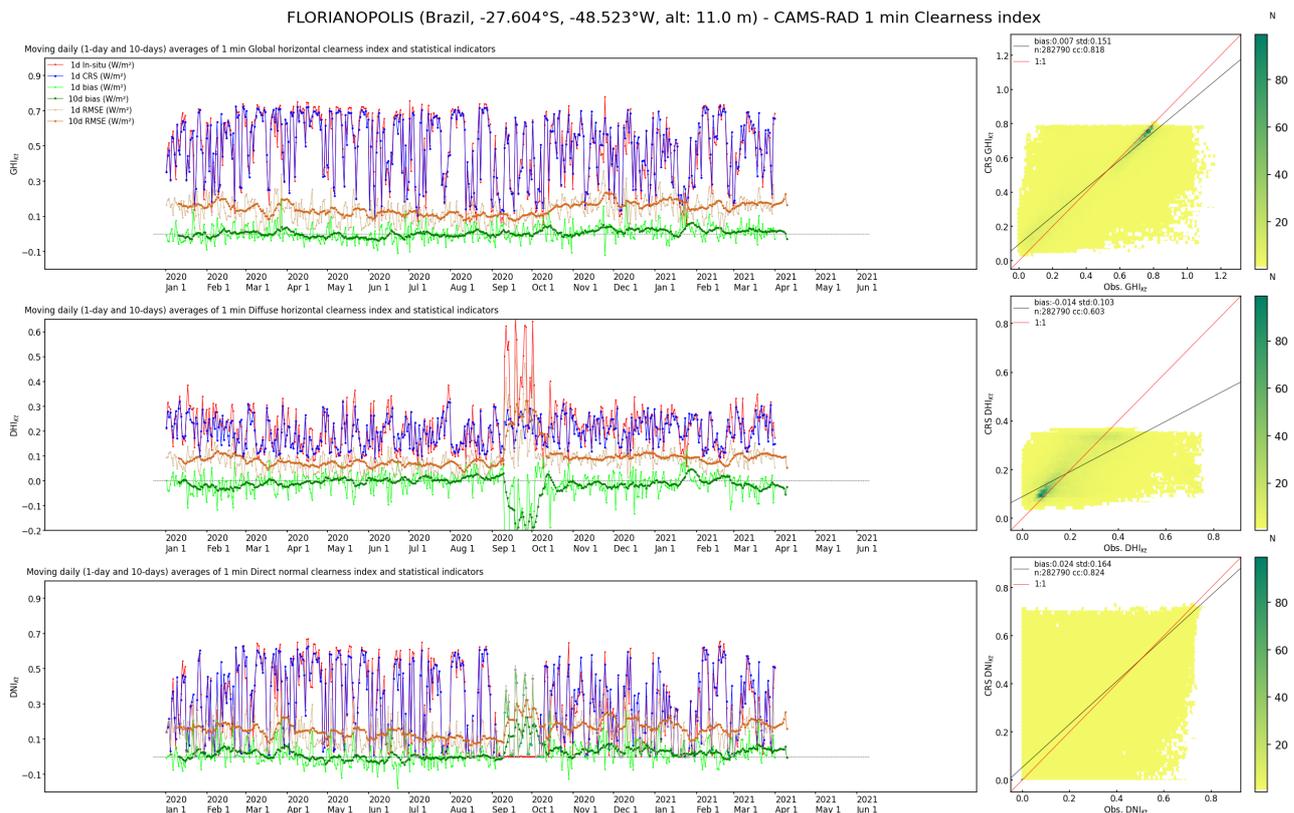


Figure 4.6. Station Florianopolis, daily and 10 days running average of clearness index From Jan. 2020 to May 2021.

Top: Global. Middle: Diffuse. Bottom: Direct normal clearness index.

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## Annex A. Procedure for validation

The validation of a product is made by comparing high quality ground measurements acquired at a measuring station. These measurements are also called observations. There are several operations to perform *a)* to ensure that the observations are of sufficient quality so that they can be considered as a reference and *b)* to adapt the different time systems and samplings.

### A.1 Controlling the quality of the observations and taking care of the time system

Time series of observation at stations have been screened for their quality according to the WMO procedure (1981) with details given in Korany et al. (2016). The automated procedure checks whether the observations exceed physically possible and extremely rare limits as well as tests of consistency between the various components of the radiation whenever possible and flags them as suspicious. Then an additional visual check is performed to further remove suspicious outliers.

Observations have been acquired in different time systems (UT: Universal Time, or TST: True Solar Time). No resampling of observations is performed in the procedure for validation. In the case of observations acquired in TST system, the procedure for collecting corresponding CRS data is as follows. Given the time stamp in TST, the times in UT for the beginning and the end of the observation are computed using the SG2 library (Blanc, Wald, 2012). In parallel, the CRS data are requested with a time step of 1 min in the UT system. The corresponding CRS irradiance is computed by summing up the 1 min data for the instants comprised between the two time limits.

### A.2 Taking care of missing observations within an hour or one day

The validation may be performed at the sampling rate of the observations, e.g., every 1 min, 2 min, 10 min etc. It may be desirable to perform the validation at a time scale that is greater than the sampling rate, e.g. 1 h or 1 day. This necessitates summing up e.g. 60 observations at 1 min to yield the hourly irradiation.

Some of these observations will be flagged out by the quality check procedure. It comes out that some data is missing in a given hour and that the hourly irradiation cannot be computed with e.g. 60 observations made every 1 min within this hour but with less than 60. Hence, the sum of the valid observations is not the actual hourly irradiation; it will be equal or less.

One solution could be to reconstruct an hourly irradiation using e.g. the hourly profile of the extraterrestrial irradiation or of the irradiation in cloud-free case. This has been examined by the Task 36 “Solar Resource Knowledge Management” of the Solar Heating and Cooling Agreement of the International Energy Agency (2005-2010), which has recommended not to reconstruct hourly or daily irradiation from measurements with gaps.



The Task 36 has recommended instead constructing pseudo-hourly irradiation or irradiance by summing up the valid observations. A similar summation for the extraterrestrial irradiation is performed for exactly the same instants. This yields a pseudo-hourly extraterrestrial irradiation. The pseudo-hourly irradiation is valid only if the pseudo-hourly extraterrestrial irradiation is equal to or greater than 0.9 times the actual hourly extraterrestrial irradiation. This constraint is set to avoid extreme cases at sunrise and sunset. Invalid pseudo-hourly observations are rejected from the analysis. The same procedure applies to the daily irradiation if needed.

Pseudo-hourly irradiations from estimates are constructed in the same way.

### **A.3 Pairing observations and estimates**

At that stage, two data sets are available. The first one contains original observations, or pseudo-hourly or pseudo-daily irradiations, depending on the case. Only valid observations have been retained. The second one is made of the original estimates, or pseudo-hourly or pseudo-daily irradiations, depending on the case. Only valid observations and estimates have been retained in these data sets.

For the sake of the simplicity, observations and estimates, respectively, will denote either the original observations and estimates, or the pseudo-hourly or pseudo-daily irradiations.

For each instant of valid observation, an observation is paired to the estimate from the product made at the location of the station and this instant. Only pairs are kept for the validation.

### **A.4 Overview of the procedure for validation**

The procedure for validation comprises two parts. In the first one, differences between estimates and observations are computed and then summarized by classical statistical quantities. In the second part, statistical properties of estimates and observations are compared.

The procedure for validation applies to irradiation or irradiance, and clearness index. The changes in solar radiation at the top of the atmosphere due to changes in geometry, namely the daily course of the sun and seasonal effects, are usually well reproduced by models and lead to a de facto correlation between observations and estimates of irradiation. The clearness index is a stricter indicator of the performances of a model regarding its ability to estimate the optical state of the atmosphere. Though the clearness index is not completely independent of the position of the sun, the dependency is much less pronounced than for radiation.

### **A.5 Computation of deviations and statistical quantities**

This part of the present protocol of validation puts one more constraint on observations.

**Before 2020Q4 validation report (until DJF 2020):**

Since the lowest values can be noise and are therefore insignificant in a validation process, any observation should be greater than a minimum significant value. If there are not, the observations, and the corresponding estimates, are removed from the data sets and are not kept for the computation of the deviations.

The threshold is selected in such a way such that there is a 99.7 % chance that the actual irradiance is significantly different from 0 and that it can be used for the comparison. It is set to 1.5 times the uncertainty of measurements of good quality as reported by the WMO (2012).

The threshold is  $30 \text{ W m}^{-2}$  (1.5 times  $20 \text{ W m}^{-2}$ ) for the hourly (or intra-hourly) mean of global or diffuse irradiance and  $7.5 \text{ W m}^{-2}$  (1.5 times  $5 \text{ W m}^{-2}$ ) for the daily mean of global or diffuse irradiance. As for the direct irradiance at normal incidence, the threshold was set to  $22 \text{ W m}^{-2}$  (1.5 times  $15 \text{ W m}^{-2}$ ) for the hourly or intra-hourly mean and  $7.5 \text{ W m}^{-2}$  (1.5 times  $5 \text{ W m}^{-2}$ ) for the daily mean.

**December 2020 - change in the validation protocol on usage of lower thresholds:**

From #30 report (MAM 2020 dataset) onwards, no threshold on irradiance value is applied to *B* anymore. A new threshold on solar elevation ( $>10^\circ$ ) is applied on all components in order to avoid horizon obstructions and directional response of pyranometers. This new protocol is based on a recent study comparing the effect of different thresholds on the validation. The results for the *B* component are presented in the report CAMS72\_2018SC2\_D72.1.6.1-2020, the Service update report 2020.

From #31 report 2021Q1 (JJA 2020 dataset) onwards, no threshold on irradiance value is applied to *G* and *D* anymore, in order to be consistent with *B*. The quality check procedure used to remove all *G* under  $50 \text{ W m}^{-2}$ , for the reason that under this value the tests cannot be performed. That also automatically removes *D* under  $15 \text{ W m}^{-2}$  approximately. Actually, it is unclear whether the data outside of the tested domain should be re-integrated into the dataset. A collaboration with the IEA PVPS task16 team for that (and other) unclear issues is foreseen. For the consistency of all components, the data outside the tested domain are re-integrated in the dataset.

Following the ISO standard (1995), the deviations are computed by subtracting observations for each instant from the estimates: deviation = estimate - observation. The set of deviations is summarized by a few quantities such as the bias or the root mean square error listed in next table. 2-D histograms between observations and estimates are drawn as well as histograms of the deviations.



## Quantities summarizing the deviations

Mean of measurements at station kept for validation	The mean of the measurements made at the station and kept for validation for this period.
Number of data pairs kept for validation	The number of couples of coincident data (CRS, ground measurements) used for validation.
Percentage of data pairs kept relative to the number of original measurements	The number of couples of coincident data (CRS, ground measurements) kept divided by the number of measurements available and greater than 0 from the station.
Bias (positive means overestimation)	The mean error for the period, i.e. the mean of the deviations. It is also equal to the differences between the mean of the CRS product and the mean of the ground measurements. The bias denotes a systematic error. Ideal value is 0.
Bias relative to the mean of measurements	The bias divided by the mean of measurements kept for validation, expressed in per cent.
RMSE	The root mean square error. Deviations are squared then averaged, and the RMSE is the root of this average. Ideal value is 0.
RMSE relative to the mean of measurements	The RMSE divided by the mean of measurements kept for validation, expressed in per cent.
Standard deviation	The bias is subtracted from each deviation. The result is squared and averaged. The standard deviation is the root of this average. It denotes the scattering of the deviations around the bias. Ideally, the standard deviation of deviations must be close to 0, and more exactly within the standard deviation of the errors of the measurements.
Relative standard deviation	The standard deviation divided by the mean of measurements kept for validation, expressed in per cent.
Correlation coefficient	The correlation coefficient between the CRS data and the ground measurements. It denotes how well the CRS product reproduces the change in measurements with time. The closer to 1 the correlation coefficient, the better the reproduction of the variability.



Formula to compute the above-mentioned quantities

	Formula
At instant $k$ , observation is $x_k$ and estimate (model) is $y_k$	
Number of samples	$N$ pairs of coincident values $(x_k, y_k)$
Mean observed value	$m_x = \frac{1}{N} \sum_{k=1}^N x_k$
Mean of the estimates $y$	$m_y = \frac{1}{N} \sum_{k=1}^N y_k$
Deviation at $k$	$\delta_k = (y_k - x_k)$
Bias (mean deviation, systematic error)	$b = \frac{1}{N} \sum_{k=1}^N \delta_k$
Relative bias	$rb = b/m_x$
Root mean square error	$RMSE = \sqrt{\frac{1}{N} \sum_{k=1}^N \delta_k^2}$
Relative RMSE	$rRMSE = RMSE/m_x$
Standard deviation of $\delta$	$\sigma = \sqrt{\frac{1}{N} \sum_{k=1}^N (\delta_k - b)^2}$
Relative standard deviation	$r\sigma = \sigma/m_x$
Relation between $b$ , $RMSE$ and $\sigma$	$RMSE^2 = b^2 + \sigma^2$
Standard deviation of $x$	$\sigma_x = \sqrt{\frac{1}{N} \sum_{k=1}^N (x_k - m_x)^2}$
Standard deviation of $y$	$\sigma_y = \sqrt{\frac{1}{N} \sum_{k=1}^N (y_k - m_y)^2}$
Covariance of $x$ and $y$	$\sigma_{xy} = \frac{1}{N} \sum_{k=1}^N (x_k - m_x)(y_k - m_y)$
Correlation coefficient	$CC = \sigma_{xy} / \sigma_x \sigma_y$

Assuming that the observations achieve the “moderate quality” pyranometer measurements defined by WMO (2008, rev. 2012) for hourly global radiation, one may ask if the CRS estimates are compliant with “moderate quality”. Defined as the 95 % probability (P95), the relative uncertainty for “moderate quality” should not exceed 20 %. The total uncertainty takes into account the uncertainty of observations and the uncertainty of the estimates. It can be expressed in a first approximation as the quadratic sum of both uncertainties. As a consequence, the total relative uncertainty should not exceed 28 % (P95), or 14 % (P66) if the estimates were of “moderate” quality.

## A.6 Typical uncertainty of measurements

The World Meteorological Organization (WMO, 2012) sets recommendations for achieving a given accuracy in measuring solar radiation. This document clearly states that “good quality measurements are difficult to achieve in practice, and for routine operations, they can be achieved only with modern equipment and redundant measurements.” The following Tables report the



typical uncertainty (95 % probability) that can be read in the WMO document. Uncertainties are expressed in  $\text{J m}^{-2}$  in the original document. The following Tables report them in  $\text{W m}^{-2}$  also.

Table A.1. Typical uncertainty (95 % probability) of measurements made by pyranometers (source: WMO 2012)

	Good quality	Moderate quality
Hourly irradiation	8 % if irradiation is greater than $0.8 \text{ MJ m}^{-2}$ . Otherwise uncertainty is $0.06 \text{ MJ m}^{-2}$ , i.e. $6 \text{ J cm}^{-2}$ , or for irradiance approx. $20 \text{ W m}^{-2}$	20 % if irradiation is greater than $0.8 \text{ MJ m}^{-2}$ . Otherwise uncertainty is $0.16 \text{ MJ m}^{-2}$ , i.e. $16 \text{ J cm}^{-2}$ , or for irradiance approx. $50 \text{ W m}^{-2}$
Daily irradiation	5 % if irradiation is greater than $8 \text{ MJ m}^{-2}$ . Otherwise, uncertainty is set to $0.4 \text{ MJ m}^{-2}$ , i.e. $40 \text{ J cm}^{-2}$ , or for irradiance approx. $5 \text{ W m}^{-2}$	10 % if irradiation is greater than $8 \text{ MJ m}^{-2}$ . Otherwise, uncertainty is set to $0.8 \text{ MJ m}^{-2}$ , i.e. $80 \text{ J cm}^{-2}$ , or for irradiance approx. $9 \text{ W m}^{-2}$

Table A.2. Typical uncertainty (95 % probability) of measurements made by pyrhemeters (source: WMO 2012)

	High quality	Good quality
1 min irradiation	0.9 % $0.56 \text{ kJ m}^{-2}$ , or approx. $9 \text{ W m}^{-2}$	1.8 % $1 \text{ kJ m}^{-2}$ , or approx. $17 \text{ W m}^{-2}$
Hourly irradiation	0.7 % $21 \text{ kJ m}^{-2}$ , or approx. $6 \text{ W m}^{-2}$	1.5 % $54 \text{ kJ m}^{-2}$ , or approx. $15 \text{ W m}^{-2}$
Daily irradiation	0.5 % $200 \text{ kJ m}^{-2}$ , or approx. $2 \text{ W m}^{-2}$	1.0 % $400 \text{ kJ m}^{-2}$ , or approx. $5 \text{ W m}^{-2}$

## A.7 Definitions of a few quantities in solar radiation

The hourly global irradiation  $G_{\text{energy}h}$  is the amount of energy received during 1 h on a horizontal plane at ground level. It is also known as hourly global horizontal irradiation, or hourly surface solar irradiation. The hourly diffuse irradiation  $D_{\text{energy}h}$  is the amount of energy received from all directions of the sky vault, except that of the sun, during 1 h on a horizontal plane at ground level, and the hourly direct (or beam) irradiation  $B_{\text{energy}h}$  is the amount of energy received from the direction of the sun during 1 h on this horizontal plane.

The hourly global irradiation  $G_{\text{energy}h}$  is the sum of  $B_{\text{energy}h}$  and  $D_{\text{energy}h}$ :

$$G_{\text{energy}h} = B_{\text{energy}h} + D_{\text{energy}h}$$



The hourly mean of global irradiance  $G_h$ , respectively direct irradiance  $B_{\text{horizontal}h}$  and diffuse irradiance  $D_h$ , is equal to  $G_{\text{energy}h}$ , respectively  $B_{\text{energy}h}$  and  $D_{\text{energy}h}$ , divided by 3600 s. If the irradiation is expressed in  $\text{Wh m}^{-2}$ , then the dividing duration is not 3600 s, but 1 h, yielding irradiance in  $\text{W m}^{-2}$ .

The hourly mean of direct irradiance at normal incidence  $B_h$  is the irradiance received from the direction of the sun during one hour on a plane always normal to the direction of the sun. See Blanc et al. (2014) for more details on the definition of the direct irradiance at normal incidence and the incidence of the circumsolar radiation.

For the sake of simplicity, the notation  $h$  is abandoned in this text from now on. The hourly means of global and diffuse irradiances are noted  $G$  and  $D$ , and the hourly mean of the direct irradiance at normal incidence is noted  $B$ .

The hourly clearness index  $KT$  is defined as the ratio of  $G$  to the hourly extra-terrestrial irradiance  $G_0$ :  $KT = G / G_0$ . The extra-terrestrial irradiance is computed here by the means of the SG2 algorithm (Blanc, Wald, 2012). The direct clearness index and the diffuse clearness index are defined in a similar way. Because the ratio of the direct horizontal to the direct normal is equal to the cosine of the solar zenith angle at both ground level and top of atmosphere, it comes that the direct clearness index is the same than the direct normal clearness index.

## A.8 Selection of cloud-free observations

Following the recommendations of Roesch et al. (2011), only ground measurements are kept which obey the following constraints:

if  $\Theta_s \leq 75^\circ$ ,  $1.08 \geq (D+B)/G \geq 0.92$

if  $\Theta_s > 75^\circ$ ,  $1.15 \geq (D+B)/G \geq 0.85$

with  $\Theta_s$  the solar zenith angle,  $D$  and  $B$  the diffuse and direct components of the global irradiance.

Two filters have been applied on the remaining ground measurements in order to retain reliable cloud-free instants (Lefèvre et al., 2013). The first one was a constraint on the amount of diffuse irradiance with respect to the global irradiance since the direct irradiance is prominent in case of clear-sky. Only those minutes for which  $D/G < 0.3$ , i.e. when the diffuse component is much less than the direct one, have been retained. The second filter dealt with the temporal variability of the irradiance. If there is no cloud, the sky should be clear for a long period. Checking this would avoid cases of broken clouds or noticeable spatial heterogeneity around the site if ergodicity is assumed. The first step of this filter was to retain only periods with enough measurements that have passed the first filter. A given instant  $t$ , expressed in min, was kept only if at least 30 % of the 1 min observations in both intervals  $[t-90, t]$  and  $[t, t+90]$  have been retained after the first filter. As a consequence, only are kept instants between sunrise +90 min and sunset -90 min.



## Annex B. Station validation reports for this quarter

The validation reports provide histograms of irradiances and clearness indices computed for both observations and CRS estimates, as well as monthly means and standard deviations of hourly means of irradiance for each month of the period.

This document only includes an example of the validation report for this quarter and for a single station (CABAUW). Similar reports for all stations listed in Table 2.1 are available in pdf format in the supplement zip archive:

[CAMS2\\_73\\_2021SC1\\_D1.3.1-2021Q4\\_annexB\\_stationwise/](#)  
[CAMS2\\_73\\_2021SC1\\_D1.3.1-2021Q4\\_annex\\_B\\_MAM2021\\_STATIONNAME.pdf](#)

### Annex B. Station CABAUW



## SOLAR RADIATION VALIDATION REPORT

### CAMS Radiation Service (CRSv4.0) - Hourly Mean of Irradiance

#### Cabauw - The Netherlands

**Latitude: 51.972°N; Longitude: 4.927°E; Elevation a.s.l.: -0.7 m**

**From 2021-Mar to 2021-May**

This document reports on the performance of the product CAMS Radiation Service (CRSv4.0) when compared to high quality measurements of solar radiation made at the station of Cabauw from 2021-Mar to 2021-May using a standard validation protocol. Thresholds for the statistic indicators are GHI, DHI and DNI  $\geq 0$  W/m<sup>2</sup> with solar zenith angle  $\leq 80^\circ$ .

*Report generated on 2021-11-26*

## I. Summary of performance



*Summary of the performances of the CRSv4.0 product for Hourly  
Mean of Irradiance at Cabauw*

	McClear			CAMS-RAD			Unit
	Global	Diffuse	Direct Normal	Global	Diffuse	Direct Normal	
Mean of measurements at station kept for validation	712	101	887	340	183	276	W/m <sup>2</sup>
Number of data pairs kept for validation	31	31	31	1005	1005	1006	
Percentage of data pairs kept relative to the number of data >0 in the period	100	100	100	100	100	100	
Percentage of data pairs kept relative to the number of valid instants in the period	3	3	3	96	96	96	%
Bias (positive means overestimation; ideal value is 0)	4	25	-29	6	-4	17	W/m <sup>2</sup>
Bias relative to the mean of measurements	1	25	-3	2	-2	6	%
RMSE (ideal value is 0)	8	30	42	63	47	106	W/m <sup>2</sup>
RMSE relative to the mean of measurements	1	16	3	18	25	38	%
Standard deviation (ideal value is 0)	7	16	31	62	47	105	W/m <sup>2</sup>
Relative standard deviation	1	30	5	18	26	39	%
Correlation coefficient (ideal value is 1)	0.998	0.652	0.756	0.956	0.884	0.938	

## II. 2-D histograms (scatter density plots) - Histogram of deviations

The 2-D histogram, also known as scatter density plot, indicates how well the estimates given by CRSv4.0 match the coincident measurements on a one-to-one basis. Colors depict the number of occurrences of a given pair (measurement, estimate). In the following, yellow is used for the least frequent pairs, with blue for intermediate frequencies and blue for the highest-frequency pairs. Ideally, the dots should lie along the red line. Dots above the red line mean an overestimation. Dots below the red line denote an underestimation. The mean of the measurements, the bias, the standard-deviation and the correlation coefficient are reported. The blue line is the affine function obtained by the first axis of inertia minimizing the bias and the standard-deviation. Ideally, this line should overlay the red line. The blue line shows the trend in error when values are far off the mean of the measurements.

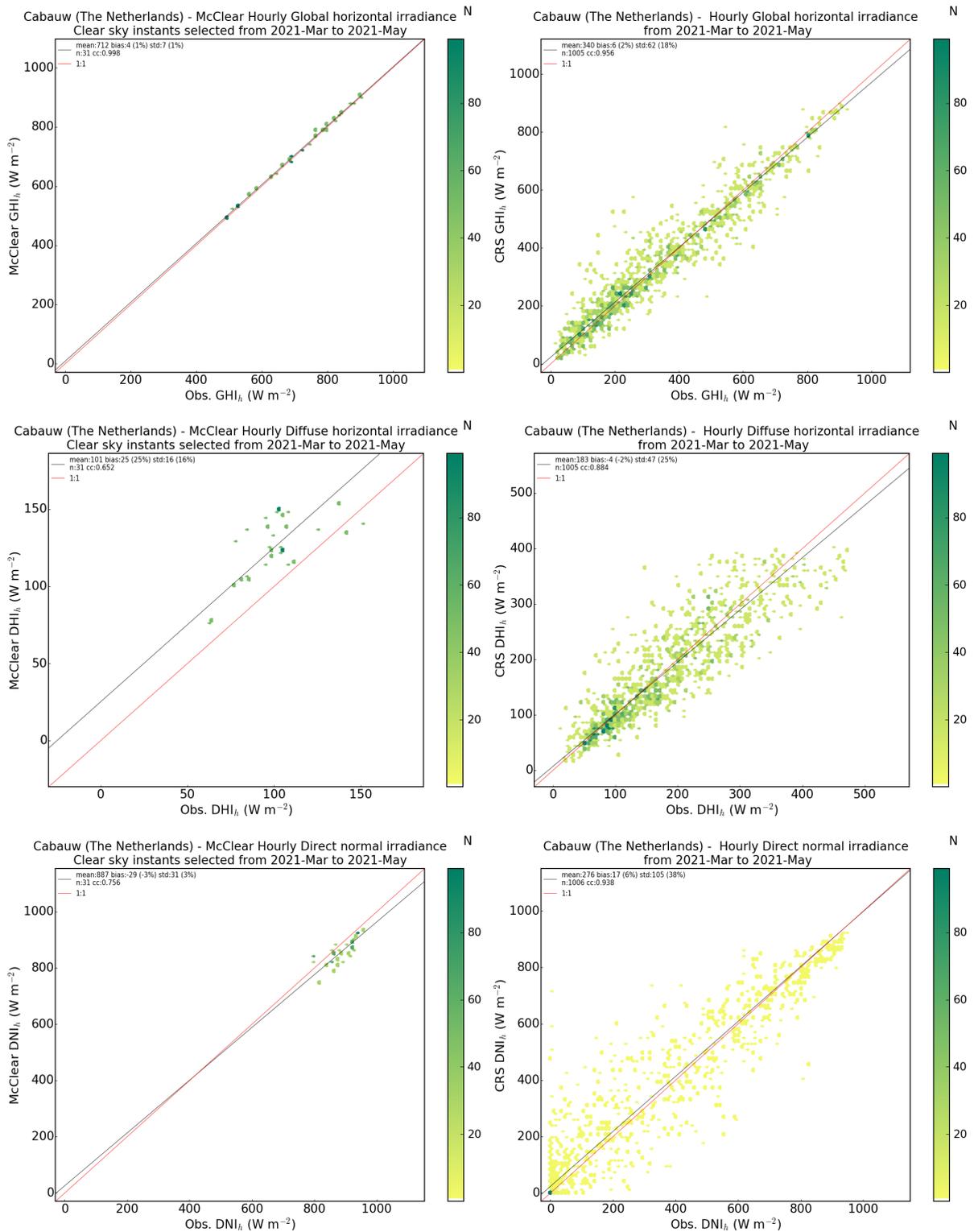
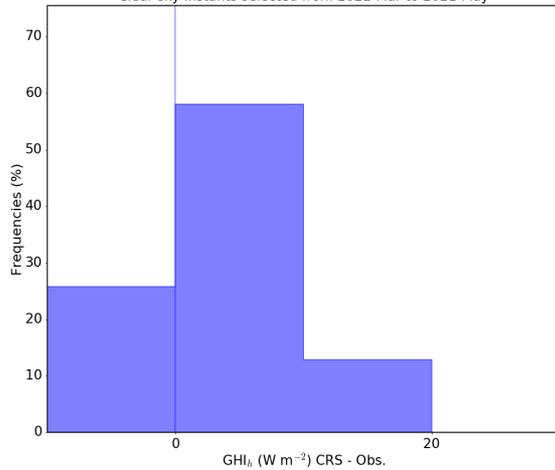


Figure 1. 2-D histogram between ground measurements (station) and the CRSv4.0 product for Hourly Mean of Irradiance. Left: McClear. Right: CAMS-RAD.

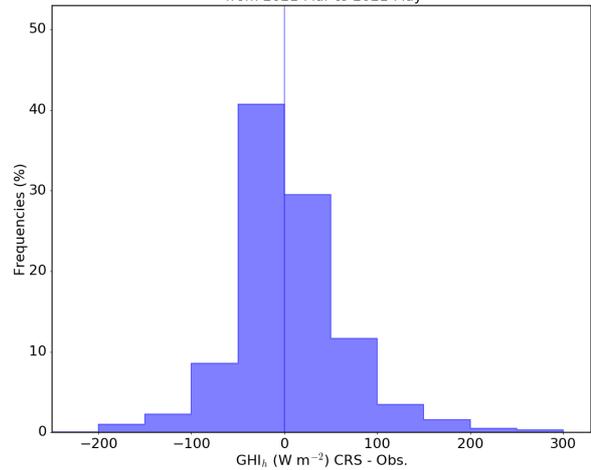


The histogram of the deviations, or as below the frequency distribution of the deviations, indicates the spreading of the deviations and their asymmetry with respect to the bias. Ideally, frequency should be 100% for deviation equal to 0. The more compact the frequency distribution of the deviations, the better.

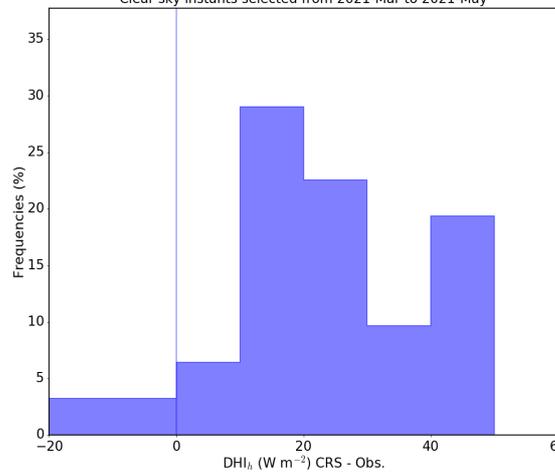
Cabauw (The Netherlands) - McClear Frequency deviation in Global horizontal irradiance  
Clear sky instants selected from 2021-Mar to 2021-May



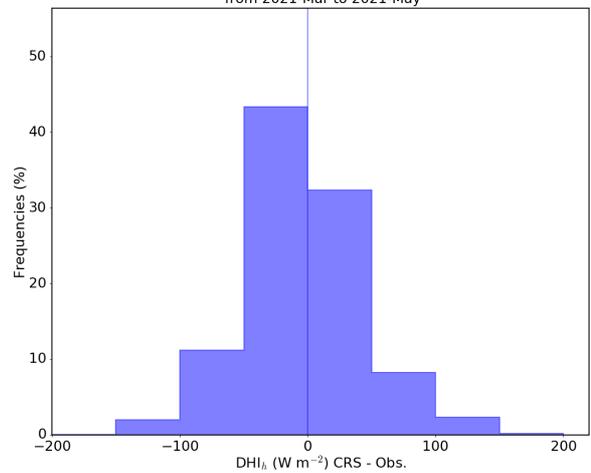
Cabauw (The Netherlands) - Frequency deviation in Global horizontal irradiance  
from 2021-Mar to 2021-May



Cabauw (The Netherlands) - McClear Frequency deviation in Diffuse horizontal irradiance  
Clear sky instants selected from 2021-Mar to 2021-May



Cabauw (The Netherlands) - Frequency deviation in Diffuse horizontal irradiance  
from 2021-Mar to 2021-May



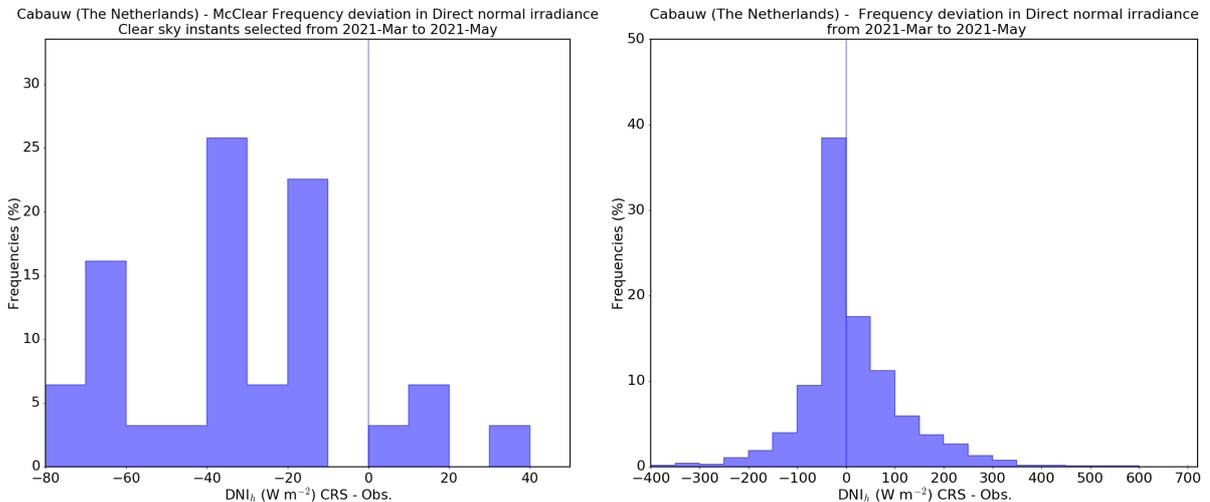


Figure 2. Frequency distribution of the deviations (CRSv4.0 - measurements). Left: McClear. Right: CAMS-RAD.

### III. Comparison of histograms

The graphs above deal with comparisons of measurements and CRSv4.0 values on a one-to-one basis: for each pair of coincident measurement and CRSv4.0 estimate, a deviation is computed and the resulting set of deviations is analysed.

This section deals with the statistical representativeness of the measurements by CRSv4.0. The frequency distributions of the measurements at station (red line) and the estimates (blue line) are computed and compared. A frequency distribution (histogram) shows how Hourly Mean of Irradiance values are distributed over the whole range of values. Ideally, the blue line should be superimposed onto the red one. If the blue line is above the red one for a given sub-range of values, it means that CRSv4.0 produces these values too frequently. Conversely, if the blue line is below the red one, CRSv4.0 does not produce values in this sub-range frequently enough.

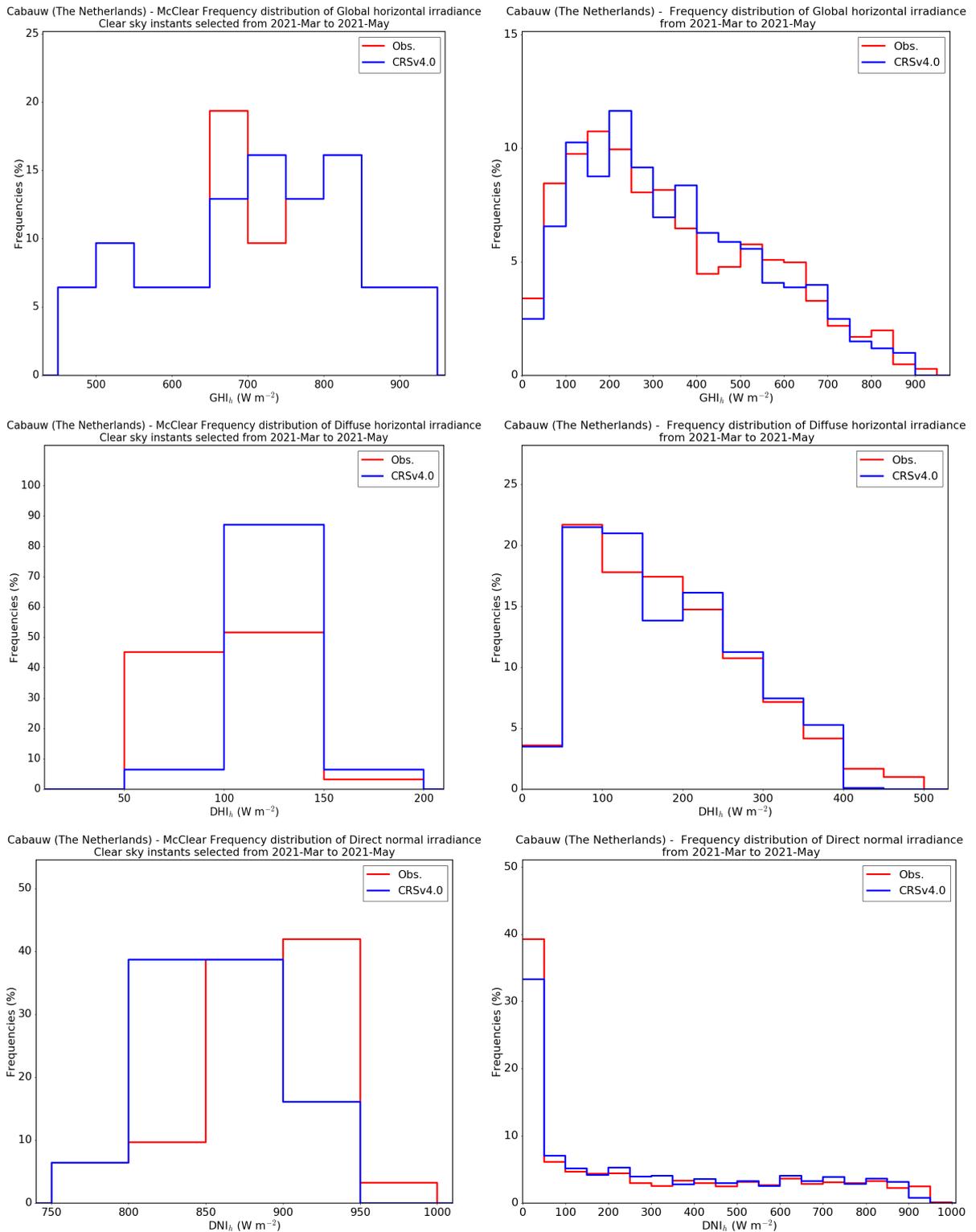
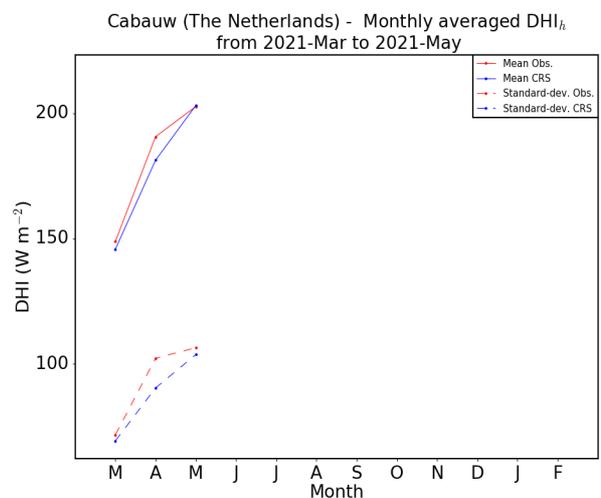
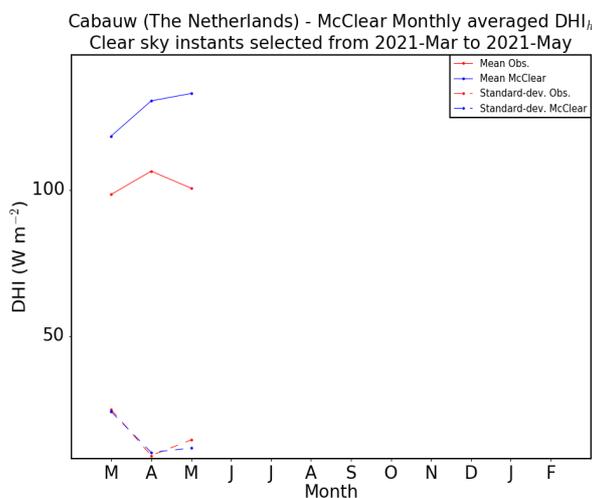
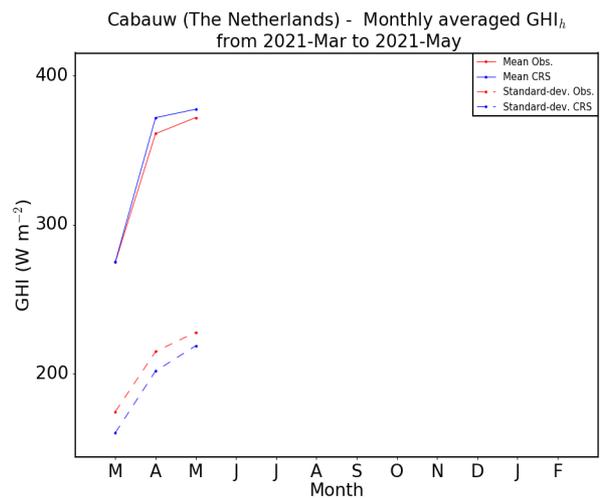
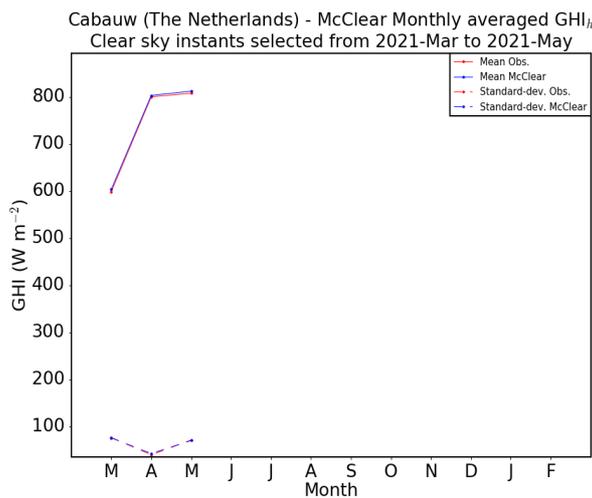


Figure 3. Frequency distributions of the measurements station (red line) and CRSv4.0 (blue line) for Hourly Mean of Irradiance. Left: McClear. Right: CAMS-RAD.



## IV. Comparison of monthly means and standard deviations

For each calendar month (i.e., Jan, Feb, Mar...) in the selected period, all measurements kept for validation and the coincident CRSv4.0 estimates were averaged to yield the monthly means of Hourly Mean of Irradiance and the standard deviations. The standard-deviation is an indicator of the variability of the radiation within a month. In the following graph, monthly means are shown with diamonds and standard deviations as crosses. Red color is for measurements and blue color for CRSv4.0. The closer the blue symbols (CRSv4.0) to the red ones (measurements), the better. A difference between red dot (measurements) and blue diamond (CRSv4.0) for a given month denotes a systematic error for this month: underestimation if the blue diamond is below the red dot, overestimation otherwise. For a given month, a blue cross above the red one means that CRSv4.0 produces too much variability for this month. Conversely, CRSv4.0 does not contain enough variability in the opposite case.



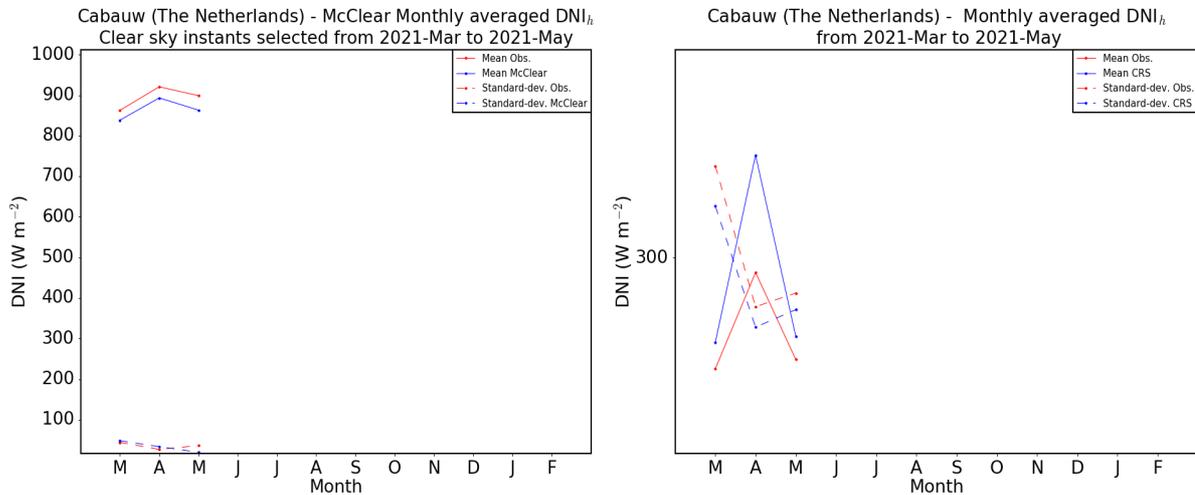


Figure 4. Monthly means of Hourly Mean of Irradiance measurements at station (red dots) and CRSv4.0 (blue diamonds), and monthly standard-deviation of measurements (red crosses) and CRSv4.0 (blue crosses). Left: McClear. Right: CAMS-RAD.

## V. Performances in clearness index

### V.1. Summary of performances

Summary of the performance of the CRSv4.0 product for Hourly Mean of Clearness Index at Cabauw

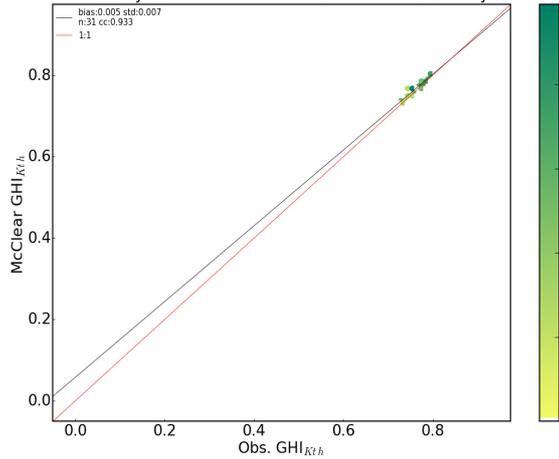
	McClea			CAMS-RAD			Unit
	Global	Diffuse	Direct Normal	Global	Diffuse	Direct Normal	
Mean of measurements at station kept for validation	0.768	0.110	0.657	0.457	0.251	0.204	
Number of data pairs kept for validation	31	31	31	1005	1005	1006	
Percentage of data pairs kept relative to the number of data >0 in the period	100	100	100	100	100	100	
Percentage of data pairs kept relative to the number of valid instants in the period	3	3	3	96	96	96	%
Bias (positive means overestimation; ideal value is 0)	0.005	0.027	-0.021	0.005	-0.007	0.012	
Bias relative to the mean of measurements	1	25	-3	1	-3	6	%
RMSE (ideal value is 0)	0.009	0.032	0.031	0.082	0.061	0.078	
RMSE relative to the mean of measurements	1	15	3	18	24	38	%
Standard deviation (ideal value is 0)	0.007	0.017	0.023	0.082	0.061	0.077	
Relative standard deviation	1	29	5	18	24	38	%



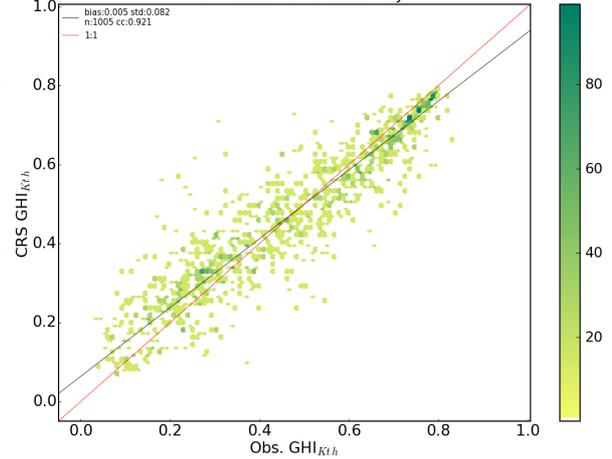
Correlation coefficient (ideal value is 1)	0.933	0.649	0.813	0.921	0.755	0.938
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## V.2. 2-D histograms (scatter density plots) - Comparison of histograms

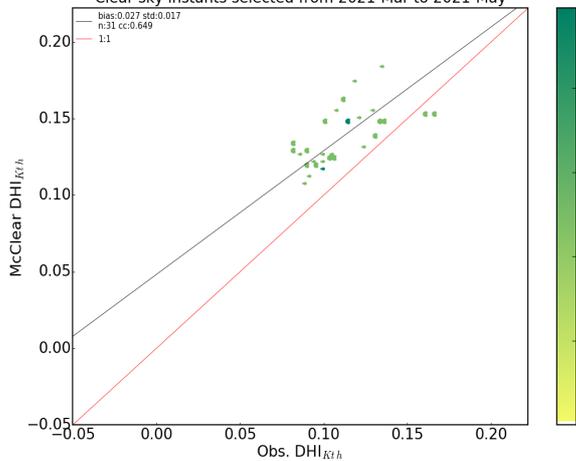
Cabauw (The Netherlands) - McClear Hourly Global horizontal clearness index  
Clear sky instants selected from 2021-Mar to 2021-May



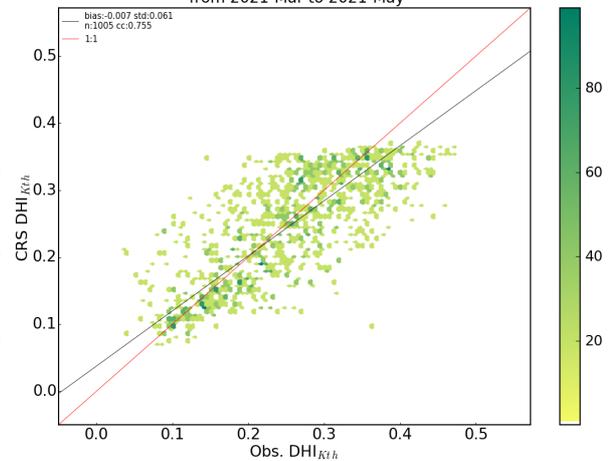
Cabauw (The Netherlands) - Hourly Global horizontal clearness index  
from 2021-Mar to 2021-May



Cabauw (The Netherlands) - McClear Hourly Diffuse horizontal clearness index  
Clear sky instants selected from 2021-Mar to 2021-May



Cabauw (The Netherlands) - Hourly Diffuse horizontal clearness index  
from 2021-Mar to 2021-May



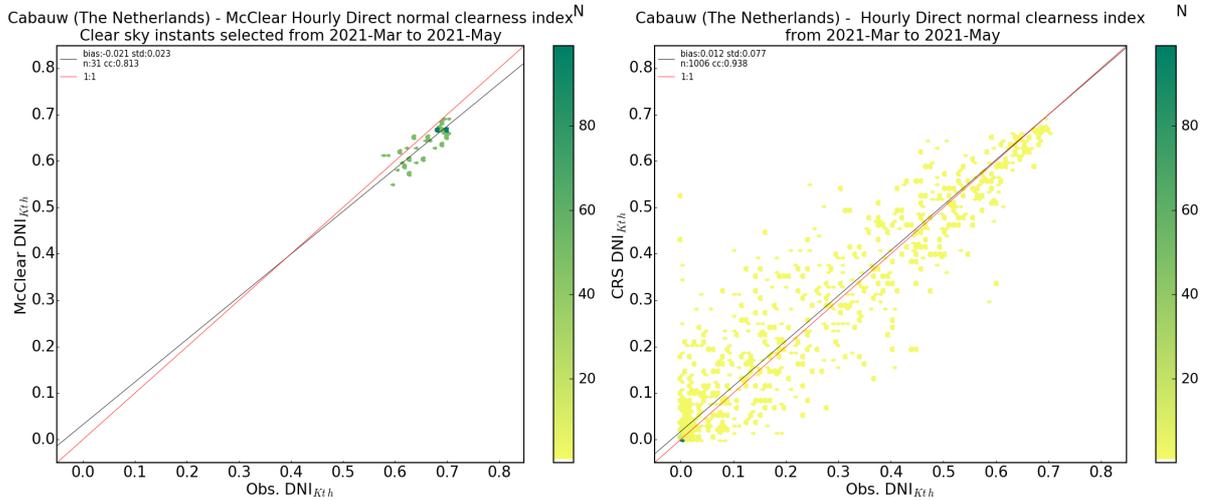
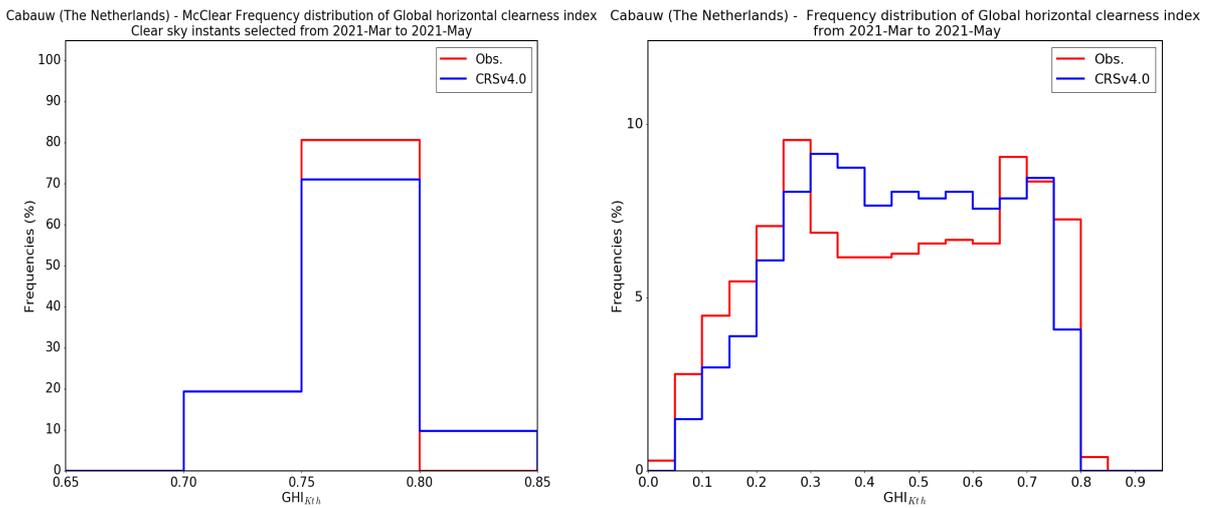


Figure 5. 2-D histogram between ground measurements (station) and the CRSv4.0 product for Hourly Mean of Clearness Index. Left: McClear. Right: CAMS-RAD.



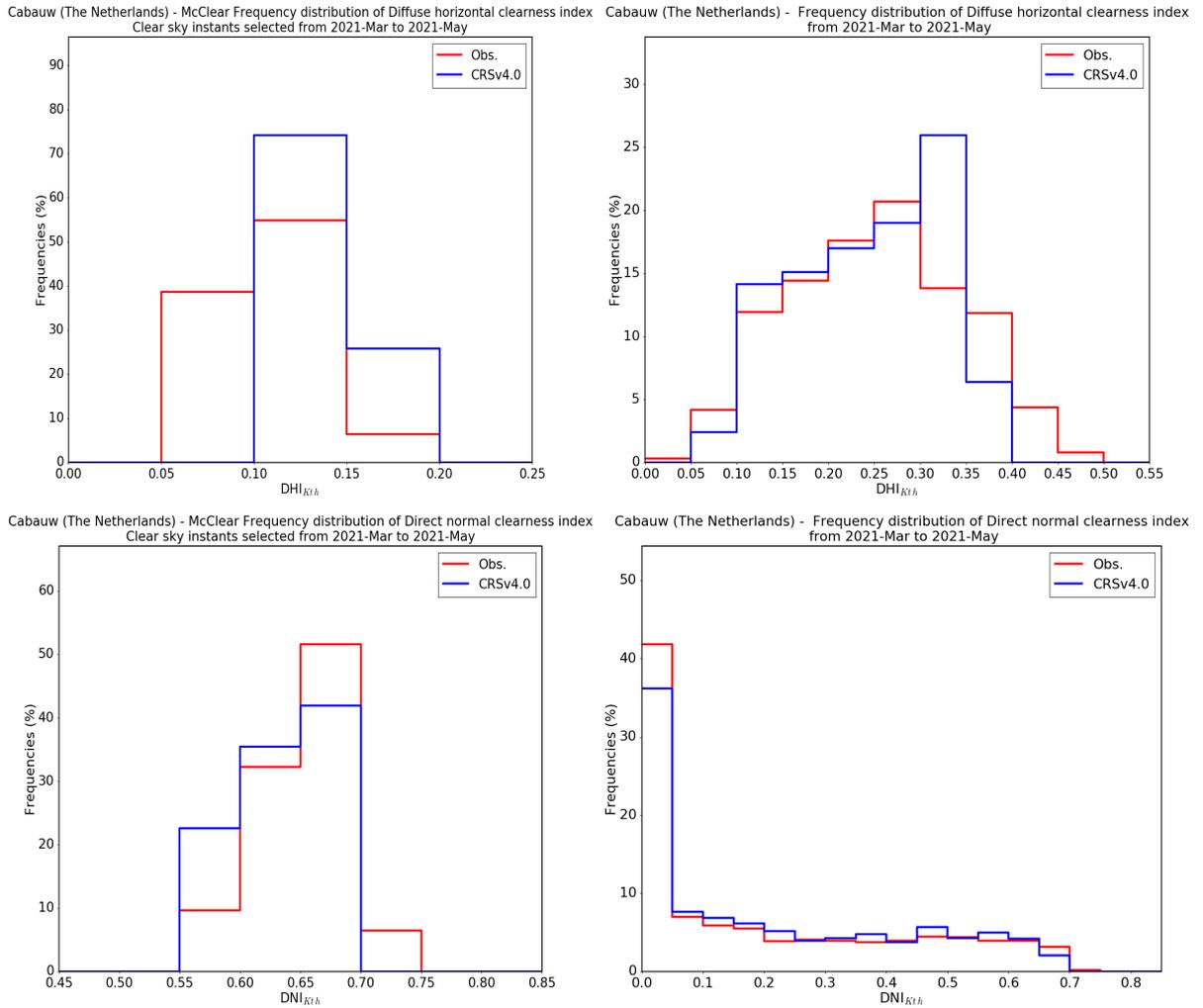


Figure 6. Frequency distributions of the measurements station (red line) and CRSv4.0 (blue line) for Hourly Mean of Clearness Index. Left: McClear. Right: CAMS-RAD.



Annex of the validation report 2021Q4. Template version regular 3.0 by Armines on Sept. 2021

