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Estimating downwelling solar irradiance at the surface of the tropical Atlantic Ocean: A comparison of PIRATA measurements against several re-analyses and satellite-derived data sets

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Running title: M. Trolliet et al.: Comparing PIRATA measurements, re-analyses and satellite-derived data.

Abstract.

This paper assesses the merits and drawbacks of several data sets of ~~the~~ solar downwelling radiation received at the surface of the tropical Atlantic Ocean where the field of solar radiation is hardly known. The data sets are compared to qualified measurements of hourly irradiance made at five buoys of the PIRATA network for the period 2012-2013. The data sets comprise the re-analyses MERRA-2 and ERA-5 and three satellite-derived data sets: HelioClim 3v5, SARAH 2 and CAMS Radiation Service v2. The re-analyses often report cloud-free conditions while actual conditions are cloudy and reciprocally, actual cloudless conditions as cloudy. The medium and high level clouds exhibit more bias than the low level clouds. The re-analyses poorly correlate with the optical state of the atmosphere derived from the measurements. The actual irradiance field is spatially distorted by re-analyses, especially for MERRA-2. Performances are similar between the three satellite-derived data sets. They correlate well with the optical state of the atmosphere and reproduce well the dynamics of the solar irradiance. The three data sets exhibit overestimation with the lowest biases reached by CAMS Radiation Service v2. The bias of HelioClim 3v5 is fairly similar from one location to the other which means that the actual spatial gradients are well reproduced.

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Introduction

reaching

The solar radiation impinging at the ocean surface is ~~known to be~~ an essential variable in the ocean-climate system (Budyko, 1969; Manabe, 1969; Siegel et al., 1995; Lean and Rind, 1998). The density of power received from the sun on a horizontal surface at ground level and per unit surface is called the downwelling solar irradiance at surface and is here abbreviated in DSIS. Other terms may be found in literature, such as solar exposure, solar insolation, solar flux, surface solar irradiance, downwelling shortwave flux, or surface incoming shortwave radiation. The DSIS intensity is large over the tropical Atlantic Ocean and influences the sea surface temperature. The net downward surface energy is positive and accumulates within the ocean ~~with a~~ resulting northward meridional transport of heat in the Atlantic Ocean (Liu et al., 2017). ~~The~~ DSIS influences the vertical structure at more rapid time scales with local impact on physics and plankton (Siegel et al., 1995).

Currently, the field of DSIS is hardly known in this area. One of the means to assess the DSIS is measuring stations such as pyranometers aboard ship or on buoys (Cros et al., 2004). Such measurements are usually accurate though the stations are sparse. They cannot offer a synoptic view of the field ~~of the~~ DSIS. Images acquired by satellites observing the ocean surface are a second means to getting a synoptic view of the temporal variations of the DSIS field. For example, the series of geostationary Meteosat satellites offer synoptic views of the tropical and equatorial Atlantic Ocean every 15 min with a spatial resolution between 3 and 5 km. Several data sets of DSIS have been constructed from these images, such as the HelioClim-3, SARAH-2 (Surface Radiation Data Set – Heliosat, version 2) and CAMS (Copernicus Atmosphere Monitoring Service) Radiation Service v2 (abbreviated in CRS) data sets which are dealt with here. in this paper

Re-analyses are a third means in which weather forecasts models are used in a re-analysis mode to reproduce what was actually observed. They assimilate state variables such as temperature, moisture and wind. On the contrary, DSIS is diagnostic, i.e. it is derived from a radiative transfer model and depends on the representation of the whole set of radiatively active variables of the atmospheric column above the point. Hence, re-analysis estimates should not be mistaken with DSIS measurements, because they include the uncertainty of the models. Of interest here are the ERA-5 developed at the ECMWF (European Center for Medium-range Weather Forecasts) and the MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, version 2) of the NASA (National Aeronautics and Space Administration) datasets.

3x sat
2x reanal

Despite the fairly recent availability of gridded data sets, their use is spreading outside the climate community and ~~there~~ is a need for validation efforts for a more informed usage of these data in ocean sciences as ~~a whole~~. This paper aims at establishing the merits and drawbacks of each of the five data sets ~~when~~ compared to qualified hourly and daily measurements of the DSIS ~~performed~~ recorded by the PIRATA (Prediction and Research Moored Array in the Tropical Atlantic) network of moorings in the tropical Atlantic Ocean, here considered as a reference. The data sets are briefly presented in Section 1. The performances are expressed as usual statistical indicators and are presented in Section 2. The merits and drawbacks of each data set are discussed in Section 3. The size of the grid cell is typically 5 km for satellite-derived data set and 50 km for re-analyses; it is large compared to a single point and this difference is discussed in Section 3. How to access the data is described in the ~~section~~ "data availability" section.

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1 Data and methods

1.1 The PIRATA measurements

The PIRATA network comprises eighteen meteo-oceanic buoys (Atlas type, progressively replaced by T-FLEX systems from 2015; refer to https://www.pmel.noaa.gov/gtmba/pirata for more information) located in the Atlantic Ocean, between the latitudes 19° S and 21° N (Bourlès et al. 2008). Each PIRATA buoy is equipped with an Eppley pyranometer mounted at a height of 3.8 m ~~and~~ that measures the DSIS. Values are recorded as 2 min averages. The sensors are deployed for about one year on average before replacement. Sensors are cleaned manually every trimester.

The measurements are subject to the same sources of uncertainty that their counterpart on a firm ground, such as incorrect sensor levelling, shading caused by close structures, dust, dew, water-droplets, bird droppings, miscalibration of sensors, electronic failures, time shifts in data loggers, maintenance mishandling, etc. (see e.g. Muneer and Fairooz, 2002). Some buoys experience accumulation of African dust, potentially leading to significant underestimation of the DSIS (Foltz et al., 2013). These authors have proposed correction for ~~such buoys~~ including sea-spray, natural and anthropogenic aerosols but limited to daily means of ~~the~~ DSIS. the data from such buoys. and correcting for.

Pyranometers view a complete hemisphere and must be horizontal for accurate measurements. This is not the case within the PIRATA network where a pyranometer is affected by the motions of the buoy which change the portion of the sky seen ~~by the pyranometer~~, inducing errors in the measurement. The errors are very complex to estimate and correct (Katsaros and DeVault, 1986; MacWhorter and Weller, 1991). They depend on the relative sun-buoy geometry which may be expressed as the tilt angle, the angle between the plane of the pyranometer and the horizontal and the difference in azimuth of the sun and tilt direction. This relative geometry is affected by wave action or strong surface current and depends on time of the day, latitude and season. Since the downward radiation received from a portion of the sky depends on the sky conditions, the errors depend also on sky conditions. Errors are most apparent in conditions of high DSIS, in cloudless skies, when solar zenithal angles are less than 60°. By ~~the~~ means of an analytical model, Katsaros and DeVault (1986) calculated the error on clear-sky days for tilts up to 10°, which are likely to occur frequently on buoys. Ignoring the reflection of the sun rays off the ocean, their calculations predict a relative error on daily average up to 10% in the tropical region. Instantaneous errors due to motions from waves can be as large, up to 10% for the hourly average for solar zenithal angles greater than 30°. ~~The~~ wave action and a preferential tilt have the least effect in the tropics. However, diurnal variations in cloudiness, which are typical at low latitudes, ~~will~~ make the compensating gains and losses uneven over the day, and ~~will~~ therefore result in a larger net diurnal error than seen (Katsaros and DeVault, 1986). MacWhorter and Weller (1991) experimentally confirmed these calculations with simultaneous measurements of irradiance by gimbaled and ungimbaled pyranometers. Systematic tilts of 10° induced by strong surface current or strong wind current yield relative errors in excess of 40%. Errors caused by wave action are less severe and may amount to 10%. Reynolds (2007) proposed an algorithm for correcting such errors. Inputs to this algorithm are the pitch, roll and heading of the sensor as well as the relative contributions of the beam and diffuse

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components to the global DSIS. Long et al. (2010) suggested a combination of a specific pyranometer and algorithm to achieve an accuracy of 10 W m-2 in 90% of the cases.

Currently, no correction is made to PIRATA measurements for ~~these~~ errors due to buoy tilt or soiling. Measurements of 2 min DSIS for the period 2004-2016 were downloaded from the ~~web site of the~~ PMEL (Pacific Marine Environmental Laboratory) ~~of the~~ NOAA (National Oceanic and Atmospheric Administration) of ~~the USA~~. Quality flags are provided together with the measurements. The NOAA procedure for quality check rejects non-plausible values, i.e. values exceeding 1400 W m 2. If any DSIS value, mean, standard deviation, or maximum, reads 0, all values are set to missing for that day. ~~In a second pass~~, flags are raised if sensor outputs are zero or full scale ~~all along~~ the day, or if the daily mean of the DSIS is outside the interval [50, 325] W m 2, or if the maximum exceeds 1350 W m 2. In a third pass, a visual inspection and comparison with time series plots from neighboring sites are performed.

An additional quality control was performed at MINES ParisTech on the top of this NOAA screening ~~for the sake of safety~~ since the PIRATA measurements serve as reference in this comparison. The quality control used here is that of Korany et al. (2016) and comprises several tests of the 2 min DSIS against extremely rare limits and physically possible limits. Values falling outside the limits were excluded from the time-series ~~for comparison~~. Eventually, a visual analysis was performed to further remove suspicious values. A noticeable fraction of the data was removed. Only measurements that passed all tests successfully were ~~kept~~. The hourly mean of DSIS was computed by averaging the 30 measurements within this hour only if all measurements were declared valid. Otherwise, the hourly mean of DSIS was declared invalid. & excluded.

Following the recommendations by Foltz et al. (2013), the buoys located north of 4° N were discarded because of the contamination by African dust and possible ~~large~~ occurrence of significant tilt due to currents. A further constraint in this study was the availability of enough measurements at each buoy ~~with no~~ major gap in a year to have an accurate description of the intra-year variability. In addition, the overlap with data sets impose to start the time period starts in 2010 as ERA-5 was only available for the period 2010-2016 at the ~~instant~~ of writing.

replace: period for which datasets overlap

~~Eventually~~ five buoys ~~were offering~~ enough hourly means of DSIS for the period 2012-2013 (Fig. 1, Table 1). In addition, the buoy 19s34w, offered also enough data in 2011, i.e. approximately 4200 measurements, and the buoys 0n10w and 6s10w had also enough data in 2010 and 2011. This ensemble of data for other years was used for further control of results and analyses.

confusingly written

first time introduced – perhaps include fig & name buoys B1 etc

Which five

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Such nomenclature is a bit awkward for the reader

Station	Latitude (positive North)	Longitude (positive East)	Number of hourly values in the time-series	Hourly mean of DSIS (W m^{-2})	Hourly mean clearness index	Daily mean of DSIS (W m^{-2})	Daily mean clearness index
0n0e	0.0	0.0	8356	449	0.48	215	0.52
0n10w	0.0	-10.0	8417	480	0.52	232	0.56
0n23w	0.0	-23.0	7431	530	0.57	256	0.62
6s10w	-6.0	-10.0	8461	485	0.53	235	0.57
19s34w	-19.0	-34.0	8541	496	0.57	243	0.61

Table 1: Geographical coordinates of the PIRATA buoys used in this study, number of hourly values in each time-series, hourly mean of DSIS and mean clearness index for the period 2012-2013. → you've mentioned hourly but also include daily.

more info.

can also use bottom as top doesn't fully give max @ surf

State why chose TOA rather than BOA

Let E be the hourly mean of DSIS and E0 the corresponding irradiance received on a horizontal plane located at the top of the atmosphere. The hourly clearness index KT is defined as the ratio of E to E0. E0 was computed here by the means of the SG2 algorithm (Blanc and Wald, 2012). As ~~Though~~ KT is not completely independent of the position of the sun, the dependency of KT on ~~with~~ the solar zenithal angle is much less pronounced than that of E. Hence, KT characterizes the optical state of the atmosphere better than E. KT is typically close to 0.8 in cloud-free conditions, and close to 0.1 in overcast conditions with optically thick clouds.

do you mean "mean" or using.

The daily means of DSIS were computed by summing up the hourly means and by dividing by 24 h. The daily clearness index was also computed in the same way as ~~than~~ the hourly KT. Table 1 reports the hourly and daily mean of DSIS as well as the means of the hourly and daily clearness indices. The means of the daily KT are greater than 0.5 denoting that the selected stations experience large occurrences of cloud-free conditions. Table 1 shows a tendency for an increase in KT from East to West. not capital.

1.2 The HelioClim 3v5 data set (HC3v5)

HelioClim 3v5, abbreviated in HC3v5, is constructed by processing images of the Meteosat second generation satellites by the Heliosat-2 method (Rigollier et al., 2004; Lefèvre et al., 2007) modified by Qu et al. (2014). It covers Europe, Africa, Middle East, parts of South America and Atlantic Ocean (full Meteosat disc). It is available from 2004 up to ~~now~~ the present with a 15 min time step. The spatial resolution depends on the pixel position and is approximately 3 km in the tropical Atlantic Ocean. Data can be accessed through a web service at the SoDa Service (Gschwind et al., 2006). This web service performs ~~itself~~ the integration over time; together with as well as the HC3v5 irradiances, it delivers the DSIS in cloud-free conditions ~~as well as~~ and the irradiance at the top of atmosphere. These three quantities were downloaded as hourly means.

full word

avoid repeat of word

rephrase

1.3 The SARAH-2 data set

The SARAH-2 data record (Pfeifroth et al., 2017a) is generated and distributed by EUMETSAT CM-SAF (Satellite Application Facility on Climate Monitoring). The data set has been obtained on the basis of observations from Meteosat first

rephrase

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word missing.

and second generation using a Heliosat-based retrieval approach (Müller et al., 2015; Pfeifroth et al., 2017b). SARAH-2 provides information on the global and direct surface solar irradiance as well as the sunshine duration from 1983 to 2015 for the full Meteosat disc. The data ~~is~~ are provided on a regular grid with a grid spacing of 0.05° x 0.05° as instantaneous values of ~~the~~ DSIS every 30 min and aggregated to daily and monthly averages. Here, the instantaneous values every 30 min were converted to hourly means by using the irradiance at the top of atmosphere.

What do you mean here? 2 values per hr used?

1.4 The CAMS Radiation Service v2 data set (CRS)

The CAMS radiation service v2 data set, abbreviated in CRS, is generated by processing images ~~of~~ from the Meteosat second generation satellite by the Heliosat 4 method (Qu et al., 2017). The geographical and temporal coverage~~s~~ as well as the spatial and temporal resolutions are the same ~~than~~ as HC3v5. Similar~~ly~~ to HC3v5, the hourly means of DSIS ~~in actual~~, and the ~~cloud-free conditions~~ clear-sky mean of DSIS as well as the irradiance at the top of atmosphere were downloaded from the SoDa Service.

-> is this referenced?

1.5 The MERRA-2 re-analysis data set

The MERRA-2 data set has many of the same basic features as the MERRA system (Rienecker at al., 2011) that has already been assessed against PIRATA daily means of ~~the~~ DSIS by Boilley and Wald (2015), but includes a number of important updates (Gelaro et al., 2017). MERRA-2 offers 72 vertical levels from ground to 0.01 hPa. The grid cell is 0.5° (approx. 55 km) in latitude by 0.625° (approx. 71.5 km at the Equator) in longitude. The temporal coverage is 1980 up to now with 1 h time step. The hourly means of DSIS in actual and ~~cloud-free~~ clear-sky conditions as well as the irradiance at the top of atmosphere were downloaded from the MERRA web site. The time series for ~~each~~ the location of each of the PIRATA buoys ~~were~~ was constructed by firstly downloading the MERRA-2 time series for the nearest four surrounding grid cells and then ~~by~~ applying a spatial bilinear interpolation technique with a weighting factor that is inversely proportional to the distance to the PIRATA site.

Rephrase

The data covers from 1980 to the present

1.6 The ERA-5 re-analysis data set

~~The~~ ERA-5 is the fifth generation of ECMWF atmospheric re-analyses of the global climate, combining models with observations (Hersbach and Dee, 2016). It has several improvements compared to ERA. It has 137 levels from the surface up to 0.01 hPa. The size of the grid cell is 31 km. It is very recent and is being released by steps. At the ~~moment~~ time of writing, the temporal coverage ~~is~~ spans 2010 ~~up to now~~ to the present with 1 h time step. The period ~~should~~ will be extended back to 1979 at the beginning of 2018. The hourly means of DSIS in actual and ~~cloud-free~~ clear-sky conditions as well as the irradiance at the top of atmosphere have been downloaded from the ECMWF MARS web site. The time series for the buoy~~s~~ locations were constructed ~~similarly~~ in a similar way to as for MERRA-2.

E.I.?

Rephrase

1.1 to 1.7] a table summarising would be useful.
-> paragraphs have a lot of repetition in text

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1.7 The CAMS cloud classification

In addition to these datasets, other variables have been downloaded to support the analyses of the errors for each data set. The CAMS Radiation Service provides a classification of the clouds in four types as a function of ~~the~~ altitude (Qu et al., 2017):

- low level cloud: water cloud at low altitude, with a base height of 1.5 km and a thickness of 1 km;
- medium level cloud: water cloud at medium altitude, with a base height of 4 km and a thickness of 2 km;
- high level cloud: deep cloud of large vertical extent from low altitude to medium altitude, with a base height of 2 km and a thickness of 6 km;
- thin ice cloud: ice cloud with a base height of 9 km and a thickness of 0.5 km.

A verbose mode is available in this service from which one may download these cloud types and other variables such as the cloud coverage, solar zenithal angle ~~or~~ and the aerosol optical properties.

2 Results

The present work followed the protocol that ~~has been~~ was designed and is used in the framework of ~~the~~ CAMS to perform quarterly validation of the CRS products against qualified ground measurements (see reports ~~from~~ by Lefèvre and Wald at https://atmosphere.copernicus.eu/validation-supplementary-products). It comprises two parts.

The first part consists ~~in~~ of the computation of differences between estimates and measurements. These differences are then summarized by classical statistical quantities. In this part, one more constraint applies ~~on~~to the PIRATA measurements: any measurement should be greater than a minimum significant value. This threshold is ~~selected~~ defined such that there is a 99.7% chance that the irradiance is significantly different from 0 and that it can be used for the comparison. It is set to 30 W m^{-2}, i.e. 1.5 times the uncertainty (percentile 95) of measurements of good quality as reported by the WMO (World Meteorological Organization, 2012). Otherwise, the measurement, and therefore the corresponding estimate, is not ~~kept for~~ included in the computation of the differences. Following the ISO standard (1995), the differences are computed by subtracting PIRATA measurements from the estimates. The set of differences is summarized by a few quantities wrong word namely the bias (mean of the differences), the standard deviation and the root mean square error. Relative values are computed relative to the mean of the corresponding PIRATA measurements for a given site. Correlation coefficients are computed. 2-D histograms ~~between~~ of PIRATA measurements and estimates, also called scatter density plots, are drawn as well as histograms of the differences.

rephrase

Statistical properties of estimates and measurements are compared in the second part. Histograms of both the PIRATA measurements and the estimates are computed, and are superimposed into a single graph. Such graphs aim ~~at assessing~~ to assess the capability of a given data set to accurately reproduce the frequency distribution of the PIRATA measurements for the period. Monthly means and standard deviations within each calendar month of both the PIRATA measurements and the estimates are computed and displayed ~~into~~ on a single graph.

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In addition to the protocol for CRS validation, other graphs have been drawn to study the dependency of the statistical indicators ~~with~~ on the irradiance or the clearness index, and other variables such as the month, year, solar zenith angle, cloud types, cloud coverage, water vapor content, the aerosol optical properties or month. → what about integrated cloud condensates?

This enhanced protocol was applied to both E and KT. ~~As for~~ Regarding the performances of a model ~~regarding~~ its ability to estimate the optical state of the atmosphere, KT is a stricter indicator than E because it is less sensitive to changes induced by the changing geometry, namely the daily course of the sun and seasonal effects. These effects are usually well reproduced by models and lead to a *de facto* correlation between PIRATA measurements and estimates of E, hiding potential weaknesses of a model. → not superscript.

daily + seasonal affects due to the Sun.

The protocol was first applied to each data set for the five buoys ~~on~~ for the period 2012-2013, ~~for~~ using hourly values. In order to better control and support the conclusions, it was also applied to: Rephrase

- each data set for the five buoys ~~on~~ for the period 2012-2013, ~~for~~ using daily values, with a threshold of 7.5 W m^{-2} instead of 30 W m^{-2},
- each data set for the buoys: 0n10w and 6s10w for 2010-2011, and 19s34w in 2011, for both hourly and daily values.

rephrase

Tables 2-4 ~~report~~ shows the correlation coefficients, biases and standard deviations of errors for each station and each data set for hourly and daily means for the period 2012-2013.

Station		HC3v5	SARAH-2	CRS	MERRA-2	ERA-5
0n0e	hourly	0.964 (0.865)	0.970 (0.877)	0.965 (0.882)	0.821 (0.486)	0.875 (0.606)
	daily	0.932 (0.927)	0.940 (0.935)	0.930 (0.925)	0.379 (0.355)	0.647 (0.599)
0n10w	hourly	0.952 (0.785)	0.965 (0.827)	0.958 (0.823)	0.858 (0.519)	0.901 (0.634)
	daily	0.874 (0.883)	0.898 (0.904)	0.898 (0.906)	0.328 (0.360)	0.547 (0.563)
0n23w	hourly	0.972 (0.811)	0.977 (0.832)	0.974 (0.829)	0.906 (0.562)	0.929 (0.641)
	daily	0.874 (0.881)	0.922 (0.926)	0.904 (0.908)	0.350 (0.386)	0.513 (0.544)
6s10w	hourly	0.968 (0.839)	0.978 (0.879)	0.970 (0.875)	0.893 (0.546)	0.896 (0.571)
	daily	0.920 (0.919)	0.945 (0.943)	0.925 (0.929)	0.485 (0.465)	0.479 (0.368)
19s34w	hourly	0.930 (0.645)	0.925 (0.627)	0.932 (0.662)	0.910 (0.560)	0.927 (0.640)
	daily	0.915 (0.803)	0.910 (0.795)	0.919 (0.813)	0.809 (0.584)	0.873 (0.705)

Table 2: Correlation coefficient observed at each PIRATA station for each data set for irradiance and clearness index in brackets

mention what you're comparing

Rephrase the sentence.

Is C.I. in brackets?

might be useful as a plot? So can see trends better?

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Station		HC3v5	SARAH-2	CRS	MERRA-2	ERA-5
0n0e	hourly	48 (10 %)	55 (12 %)	31 (6 %)	-42 (-9 %)	25 (5 %)
	daily	23 (10 %)	27 (12 %)	15 (6 %)	-20 (-9 %)	13 (5 %)
0n10w	hourly	49 (9 %)	55 (11 %)	36 (7 %)	-17 (-3 %)	25 (5 %)
	daily	23 (10 %)	26 (11 %)	17 (7 %)	-8 (-3 %)	12 (5 %)
0n23w	hourly	30 (5 %)	27 (5 %)	17 (3 %)	-10 (-1 %)	-6 (-1 %)
	daily	14 (5 %)	12 (4 %)	7 (2 %)	-5 (-2 %)	-3 (-1 %)
6s10w	hourly	40 (8 %)	41 (8 %)	28 (5 %)	12 (2 %)	15 (3 %)
	daily	19 (8 %)	20 (8 %)	13 (5 %)	6 (2 %)	7 (3 %)
19s34w	hourly	31 (6 %)	11 (2 %)	10 (2 %)	23 (4 %)	-10 (-1 %)
	daily	15 (6 %)	5 (2 %)	5 (1 %)	11 (4 %)	-5 (-2 %)

Table 3: Bias (W m^{-2}) observed at each PIRATA station for each data set (relative values in brackets)

again p 6

rephrase (caption)

Station		HC3v5	SARAH-2	CRS	MERRA-2	ERA-5
0n0e	hourly	80 (17 %)	72 (16 %)	77 (17 %)	166 (36 %)	141 (31 %)
	daily	19 (8 %)	18 (8 %)	19 (8 %)	55 (25 %)	40 (18 %)
0n10w	hourly	93 (19 %)	79 (16 %)	86 (17 %)	151 (31 %)	128 (26 %)
	daily	22 (9 %)	20 (8 %)	20 (8 %)	52 (22 %)	38 (16 %)
0n23w	hourly	73 (13 %)	65 (12 %)	68 (12 %)	129 (24 %)	112 (21 %)
	daily	17 (6 %)	14 (5 %)	15 (5 %)	41 (16 %)	31 (11 %)
6s10w	hourly	77 (15 %)	62 (12 %)	74 (15 %)	134 (27 %)	132 (27 %)
	daily	18 (7 %)	15 (6 %)	17 (7 %)	41 (17 %)	41 (17 %)
19s34w	hourly	118 (23 %)	118 (23 %)	112 (22 %)	128 (25 %)	115 (23 %)
	daily	27 (11 %)	28 (11 %)	26 (10 %)	40 (16 %)	33 (13 %)

Table 4: Standard deviation of errors (W m^{-2}) observed at each PIRATA station for each data set (relative values in brackets)

→ what definition of stdev did you use → stdev. of errors ??

The numbers in these Tables are discussed in Section 3. The correlation coefficients, biases and standard deviations of the errors for the hourly *E* and *KT* for the period 2012-2013 given in these Tables are similar or close to those for 2010 and 2011 (not presented). As expected, on (one) may note that for a given data set and a given PIRATA site, the numbers in these Tables are consistent between hourly and daily values: the relative biases are the same for the hourly and daily means, and the standard deviations of errors are greater for hourly values than for daily values. As expected, the correlation coefficients for daily *E* are less than for hourly *E* because of the strong influence of the solar zenithal angle on the correlation coefficient which creates a *de facto* correlation of hourly values between estimates and measurements. As a consequence, the discussion in Section 3 will focus on the hourly values for the period 2012-2013. The other cases may be invoked on an *ad hoc* basis to underline divergences if any.

→ what do you mean here? ??

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Results section should indicate what you've plotted before being discussed in Section

3 Discussion

3.1 The HelioClim-3 v5 data set

The HC3v5 estimates correlate very well with the measurements. The correlation coefficient ranges between 0.93 and 0.97 for E and between 0.79 and 0.87 for KT, except at 19s34w (0.65) (Table 2). The bias ~~for~~ in E is large and positive (overestimation). It ranges between 30 and 49 W m^{-2} (Table 3). Though a weak decrease from East to West may be detected in Table 2, the bias is almost the same for the five sites; the difference between the maximum and the minimum is 19 W m^{-2}. This indicates a systematic error that is fairly constant in space, meaning that the actual irradiance field is not noticeably distorted by HC3v5 and that the actual spatial gradients are well reproduced. Combined with the large correlation coefficients, this means that ~~the~~ the time-series of ~~the actual field of~~ E are well reproduced though amplitudes of variation in space and time may be hampered by the large standard deviation of the errors that ranges between 77 and 93 W m^{-2}, with a much greater value (118 W m^{-2}) at 19s34w (Table 4). This finding is consistent with those of Bengulescu et al. (2017) who reported very high correlation coefficients between HC3v5 and in situ measurements at various temporal scales, from days to years.

do you mean spatial? but

rephrase → ... pattern may not be distort but values biased

needs rewriting / not well explained.

The 2D histograms reveal a well aligned distribution with small scattering for both E and KT with an overall overestimation. Figures 2a and 2b ~~exhibit~~ show the 2D histograms for the site 6s10w. ~~The smallest~~ Irradiances less than 100 W m^{-2} are underestimated ~~and~~ while those greater than 800 W m^{-2} ~~exhibit much less overestimation and~~ are more correctly estimated. HC3v5 ~~calls upon~~ uses the McClear model to estimate the DSIS in cloud-free conditions. This model exploits the properties of the atmosphere ~~delivered~~ described by CAMS. The present results are consistent with several publications that have underlined the good quality of the McClear estimates when compared to high-quality measurements performed at terrestrial stations (Eissa et al., 2015; Lefèvre et al., 2013; Lefèvre and Wald, 2016; Marchand, et al., 2017). The clearness indices for HC3v5 show a tendency to overestimate ~~the actual~~ KT in general and to underestimate the ~~greatest~~ largest KT. HC3v5 predicts too many cases of cloud-free when cloudy; the opposite case is also true but less frequently.

rephrase → which values? Have you much data

Which figure?

rephrase plus what type of cloudy?

The frequency distributions of measurements are well reproduced by HC3v5 for E (see Fig. 3a for the site 6s10w), though one may note an overestimation of the frequencies in the range [800, 1000] W m^{-2} for stations 0n0e and 0n10w. As for KT, there is a tendency ~~to~~ towards a slight underestimation of frequencies by HC3v5 in the interval [0.4, 0.6] and an overestimation around 0.7 (see Fig. 3b for the site 6s10w). The monthly means of the estimated E are overestimated ~~those of~~ compared to the measurements at all sites, except in June and July when they are similar (November for 19s23w) (see e.g. Fig. 4a for the site 6s10w). The situation is more confuse for the monthly standard deviations which are similar or close for three stations and overestimated at the two other stations, except for April to September when they are close.

in what range? → not shown

As for the daily DSIS, the correlation coefficients for daily KT are greater than for hourly KT, close to 0.9 (0.80 at 19s34w), and similar to those for the daily E (Table 2). Contrary to the smallest hourly irradiances which are underestimated, the smallest daily irradiances (<300 W m^{-2}) are overestimated; otherwise they are well estimated (not shown). In conclusion,

figs not referred to could go in an appendix