The APOLLO cloud product statistics service

Introduction

DLR and Transvalor have prepared a new service to disseminate the statistics of the APOLLO cloud physical parameters as a further help in the characterization of a solar site. This service preparation phase was done with the help of a grant from ESA[1]. The project is named RESGrow and has its web site at http://resgrow.eu/.

This document presents the APOLLO cloud physical parameters computations and the different statistics based on this computation which will be exposed to the user by the service. The service is delivered as a pdf report showing a set of statistics for a given location. The report can also show a comparison of these statistics for different locations to compare alternative locations for a power plant development or to decide about the representativeness of a local ground measurement for a site some kilometers or even tens of kilometers away. A similar comparison can be made for different periods of time at the same location. This may allow the assessment if the period with available ground measurements is representative for the long-term conditions at a site or to investigate any time period where any doubt about the quality of an existing ground measurement may occur.

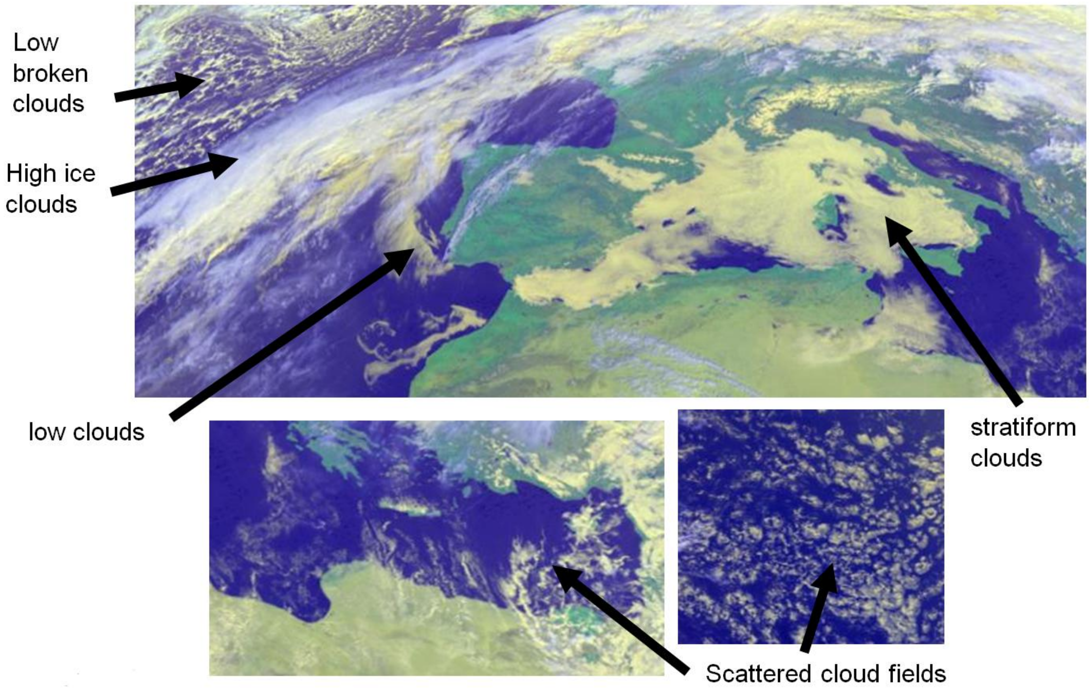
Two products will be delivered:

- The first product is a set of “simple” clouds statistics. It will be the ideal companion of an irradiation long term time series analysis, adding useful information to understand better the average climatology at the site location. It will thus be possible to know when and how much the different types of clouds are present either during the day or during the year’s months. It will be possible to answer questions like “how much and how often are there cumulus development in the afternoon” or “are there often high cirrus which cannot be detected by a lowering of the Global Horizontal Irradiation but are detrimental for a CSP technology”.
- The second product is a full set of statistics, with inter site comparisons and inter period comparisons. This is the companion of an in-deep site analysis, very important for sites with complex skies or for sites where a CSP installation is planned.

The APOLLO methodology at a glance

The APOLLO methodology uses multiple spectral channels of the METEOSAT Second Generation satellite (MSG) to discriminate between different cloud types.

[1] contract 4000107680/13/I-AM; Expansion of the market for EO Based Information Services in waste management, renewable energy and ecosystem services assessment



Copyright: EUMETSAT/DLR

Below a picture of water/mixed phase clouds as seen from the ground is shown on the left image and an example for optically thin ice clouds is given on the right image. It is expected that for water/mixed phase clouds in such an overcast case as being shown, both the global and the direct irradiance become low together with a low temporal variability.
For a more scattered case of water/mixed phase clouds (not shown), the global irradiance varies quickly between medium and high values and even overshooting values above clear sky values occur. Opposite to the overshooting situation, the direct irradiance jumps between zero, medium and high clear sky-like values.
For optically thin ice clouds, the situation is different: For global irradiances the influence is low and any temporal variability is typically fast, but low in the amplitude. On the other hand, direct irradiances are affected very significantly, with typically medium and high values together with a high fluctuation rate.

Karlsruher Wolkenatlas, copyright B. Mühr

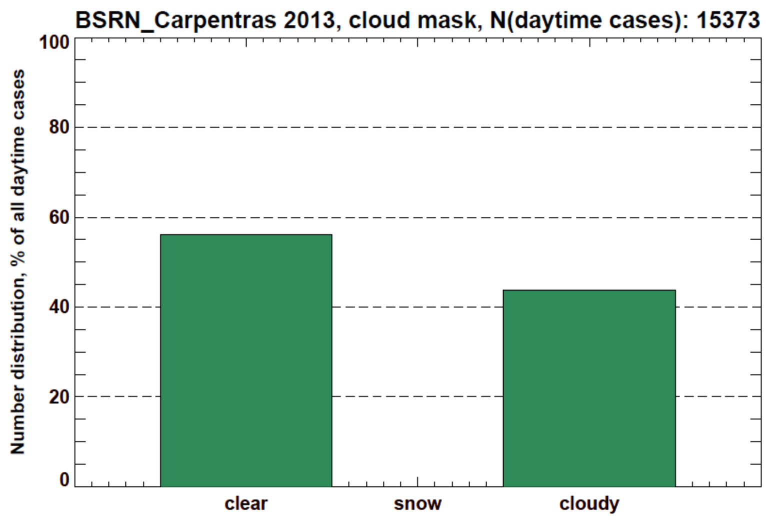
The APOLLO methodology delivers cloud mask, cloud optical depth, liquid and ice water path, and cloud top temperature as cloud parameter products for each MSG SEVIRI pixel in a temporal resolution of 15 minutes during daytime, for the period 2004-2014 (10 years). The covered zone is [60°N,60°S,60°E,60W], with a resolution of 3x3 km2 at the nadir of the satellite [0°, 0°]. The resolution in Europe is about 4x5 km2 to 5x6 km2. The following parameters are computed and stored:

- Cloud mask and snow
- Cloud coverage (0-100%)
- Cloud type (low, medium, high water/mixed water/ice phase clouds; optically thin ice clouds)
- Cloud optical depth
- Cloud top temperature

Main statistics delivered by the Apollo WEB service for solar plant sitting, operations planning or operations monitoring – Examples and their interpretation

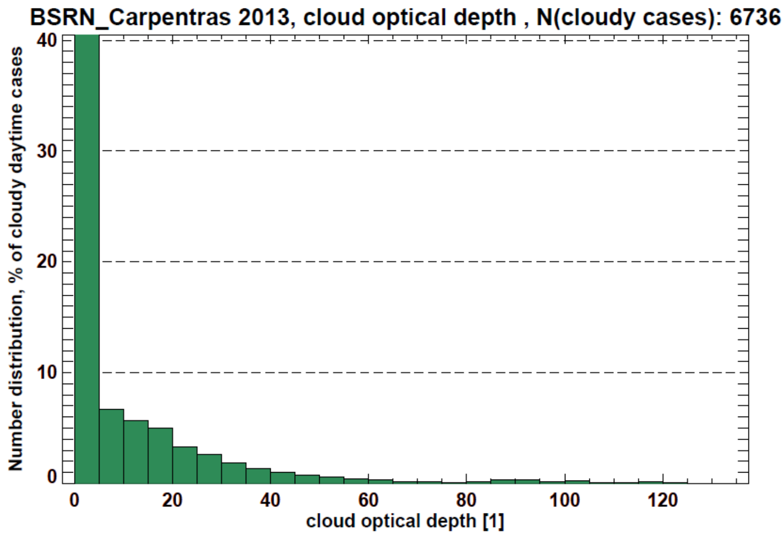
Cloud mask

This very basic statistic shows that in the Carpentras (France) location pixel considered, for the year 2013, about 55% of the time slots were clear, 45% cloudy and 0% with snow on the ground. Cases with snow on the ground typically represent cases where also photovoltaic panels might be covered with snow resulting in a low yield while the global irradiance is high as it is a cloud-free situation.



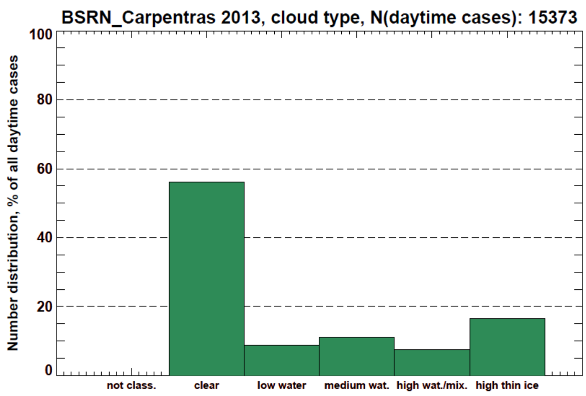
Cloud Optical Depth

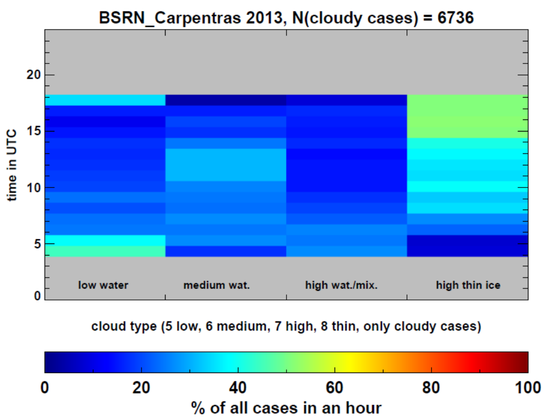
The cloud optical depth represents the opacity of clouds. For Carpentras (France), we can see that over 40% of the cloudy cases have a low optical depth below 5. There is no significant proportion of cases with very thick and opaque clouds (optical depth above 50) as it would be typical e.g. for tropical regions.



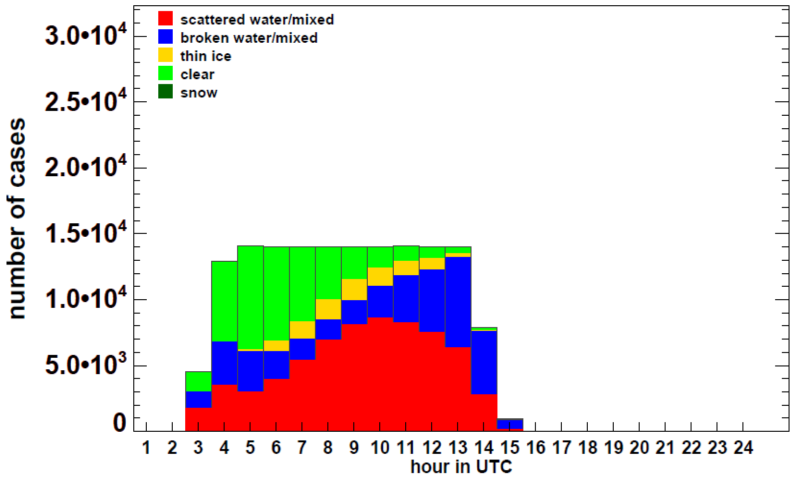
Cloud type

The cloud type of low, medium or high level water/mixed phase clouds or optically thin ice clouds can be represented as a global number distribution for all the time slots or as a 2D histogram showing the changes in cloud type as a function of the hour of the day. In Carpentras and for the year 2013, 15% of the day time, there are high thin ice clouds. This cloud type is not filtering much of the Global Horizontal Irradiation and thus does not impact much a PV plant producible, but it can have a very high impact on the Direct Normal Irradiation and the producible of a CPV/CSP plant. The 2D histogram shows also that these high thin ice clouds appear mostly at the end of the day. Besides the certainly given usefulness of such an analysis we would also like to give a short warning: For low water clouds any maximum of values of occurrence only in the first 1-2 hours after sunrise or before sunset can be an effect of low retrieval accuracy in low sun elevation cases depending on the location of interest.

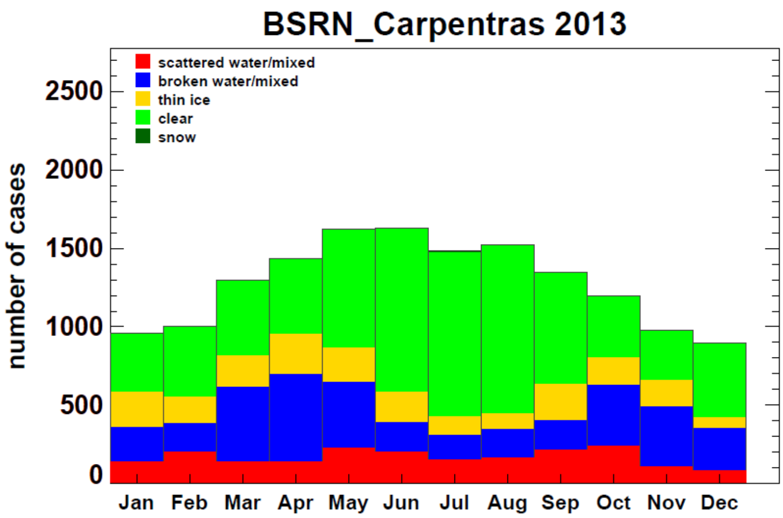




It is also interesting to see if there is a daily or annual pattern on the cloud type evolution. This is shown with the average daily or monthly evolution stacked bar graphs – here based on 10 years from 2004 to 2013. The next figure represents daily evolution for a site in La Réunion Island. It shows clearly that clear sky moments were the irradiation will be at its maximum, are predominant in the morning and that broken or overcast water/mixed phase clouds are very often generated in the afternoon, a typical situation for a tropical location. Also, scattered water/mixed phase clouds are generated due to local convection during the morning and show a maximum in the early afternoon hours.



The average monthly cloud type evolution in Carpentras shows more both scattered and broken/overcast water and/or mixed water/ice phase clouds in spring and autumn which are the typical rainy periods in this south of France region.

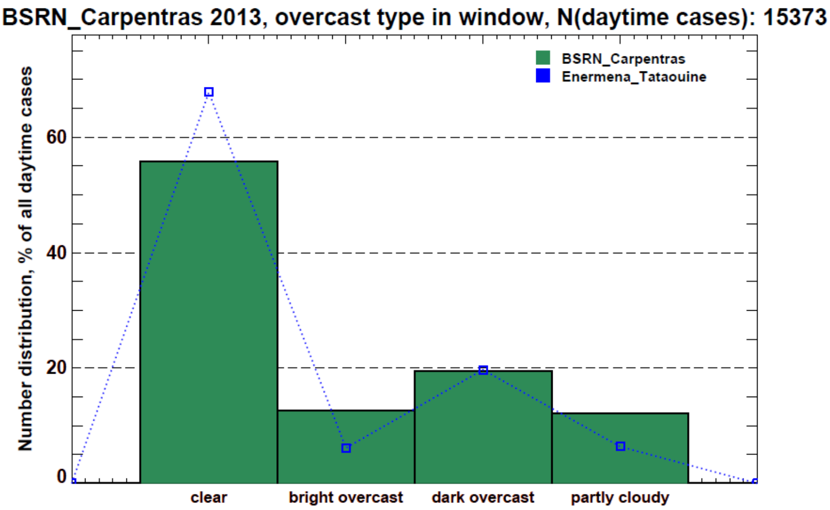


Cloud overcast type

With the computed APOLLO data at the pixel location of interest, it is possible to classify the cloud overcast type and use it for instance to optimize a photovoltaic panel tilt angle or to give additional information for DNI dependent solar installations.
Armstrong et al. (2010) shows that the optimum tilt angle (OTA) is a function of latitude in cloud free regions of the sun belt with dominating DNI and that in regions where the diffuse part dominates (> 45°N) the OTA is smaller. OTA becomes a function of latitude, frequency of clouds and their type. Armstrong suggests a classification into clear, bright overcast, dark overcast and partly cloudy based on ground observations of the cloud situation. Following these suggestions, we have derived a satellite-based 'viewing from above' classification discriminating especially dark from bright overcast situations. They are defined as follows:

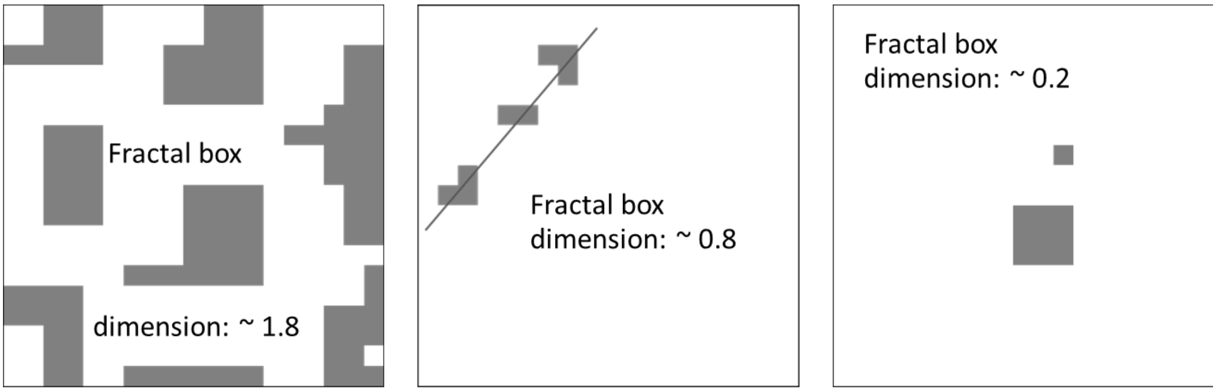
- clear = at least 90% cloud free pixels in a local surrounding; a clear pixel is defined as having max 10% cloud coverage.
- bright overcast = more than 50% of the local surroundings are cloudy pixels, but at least 20% of them are thin ice clouds only
- dark overcast = more than 50% of the local surroundings are cloudy pixels, and more than 80% of them are not thin ice clouds
- partly cloudy = the rest

The next figure shows a comparison in 2013 for this information between Carpentras and Tataouine (Tunisia). The Tataouine site is a desert and has more clear sky moments and less bright overcast. It is thus naturally more suited for a CPV/CSP type solar plant. Bright overcasts is a typical situation with a sharp decrease of the DNI due to the diffraction of the direct irradiation (and the increase of apparent the sun disk angle), even though there is no very noticeable decrease of the GHI. Partly cloudy cases on the other hand typically show a large temporal variability between zero and clear sky irradiance values.



Cloud scatteredness

The analysis is extended further in a 29x29 pixel window around the location of interest. In this window, several values are computed, mostly the number of cloud elements and the cloud shape complexity from the fractal box counting dimension. This fractal box counting dimension represents the complexity of the clouds shape and evolves from zero (a point) through one (a line) to two (an area). In most cases, it lies between one and two if the cloudy pixels clusters in the window are several pixels wide. The figure below shows typical examples of these situations.

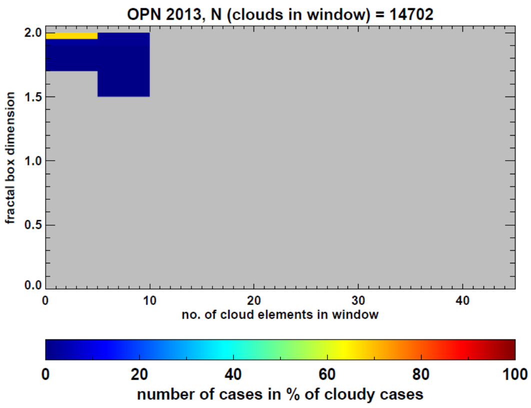


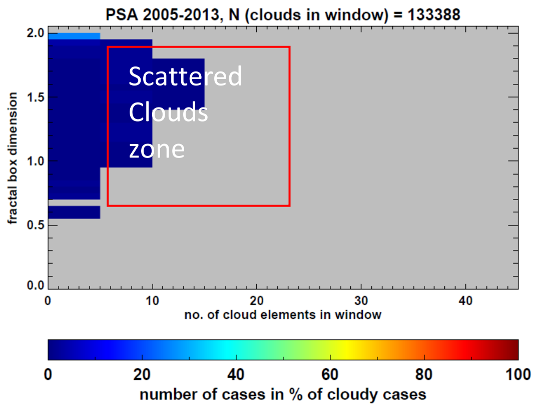
Source: S. Glas (2014)

Specific combinations of these two parameters (number of clouds elements and fractal box dimension) can be used to define a cloud compactness indicator and are summarized in the following table:

Fractal box dimension	# of cloud elements	Cloud compactness indicator
2	1	Overcast
1.7 to 1.9	<=5	Nearly overcast clouds
1.8 to 2	>5	Broken clouds
0 to 1.7	<=5	Isolated clouds
0.5 to 1.8	>5	Scattered clouds

With these elements, a 2D histogram (for the cloudy time slots only) is plotted which gives a global information on the aspect of the cloud cover at the location when clouds are present in the area. Below are two examples of the results, the first one for Oberpfaffenhofen (OPN, Germany) and the second one for PSA (Plataforma Solar de Almeria in Spain).





In OPN, the cloudy days are mostly overcast (the yellow spot on the top left corner of the plot) or with a few large/nearly overcast clouds or broken clouds. In PSA, the scattered clouds or isolated clouds skies are more frequent – the scattered clouds zone is populated much more. In case of scattered cloud cases, the number of small clouds can reach much higher values than in OPN.

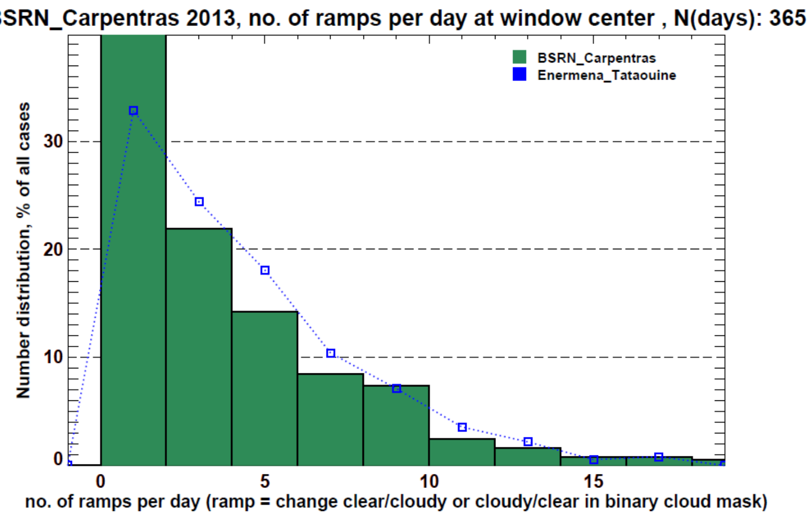
For the scattered cloud cases, the consequences on the PV or CSP systems can be multiple:

- Overshooting of global irradiances

    - ramps in irradiance within seconds
    - power converter outside optimum efficiency range
- Rapid changes in direct irradiance
    - non-linear effects in heat transfer fluids
    - fast temperature changes on solar tower receivers
- Power output of distributed PV generation
    - change of PV production summed up on transformer level
    - ramps of PV generation causing difficulties in the electricity grid

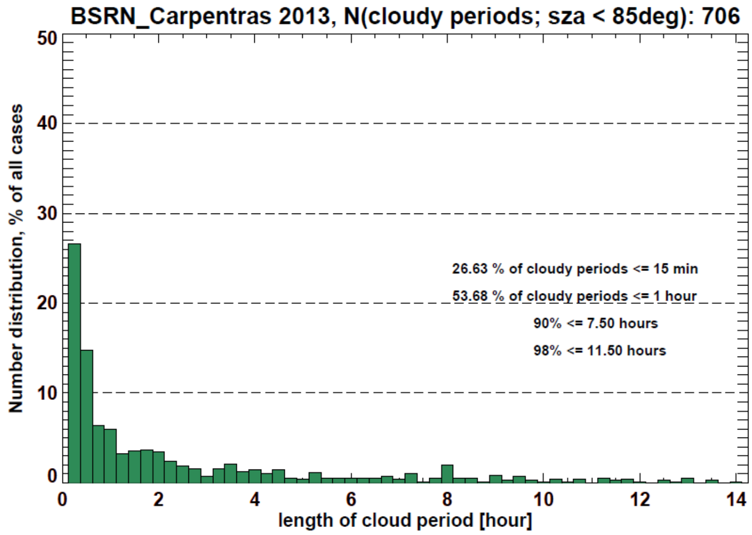
Ramps

In our context we define a ramp as a change from cloudy to clear and vice versa in the cloud mask at the pixel location, from one time slot to the next in their 15 minute temporal resolution. On request, a 5 min temporal resolution dataset is also available in Europe and Northern Africa from the rapid scan mode of the MSG satellite. The number of ramps per days is an important parameter for the system definition. It can reduce the performance of a CSP system or necessitate a short term electricity storage system even for a PV plant to ensure the stability of the electricity output and the safety of the inverters.
The figure below compares the distribution of the number of ramps per day in 2013 for Carpentras (France) and Tataouine (Tunisia). It shows that Tataouine has a slightly higher number of day cases with 2 to 12 ramps per day.

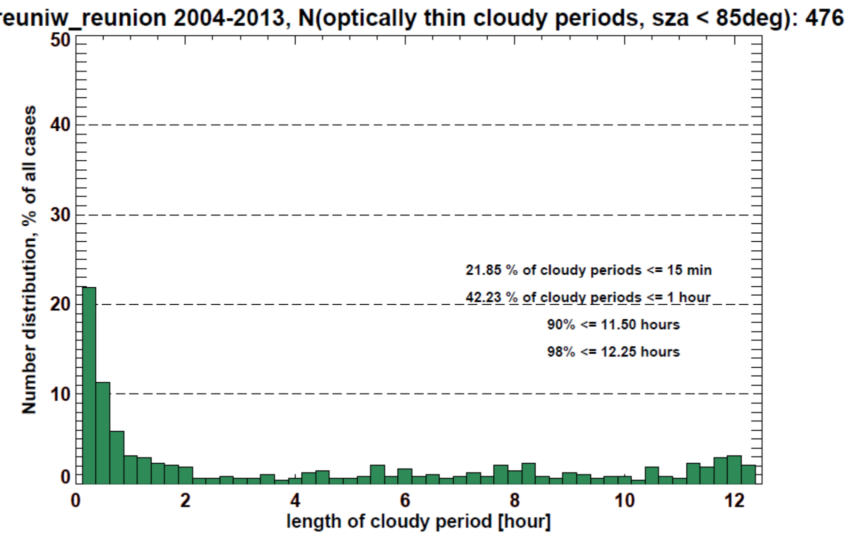


Duration of cloudy periods

The typical duration of a cloudy period can be a useful information e.g. in storage dimension or hybrid power plant design. In Carpentras, it shows that when clouds are present, they last less than 1 hour in 54% of the cases. This histogram is computed from all cloudy periods and when the sun zenithal angle SZA is lower than 85° (sun elevation above 5°).



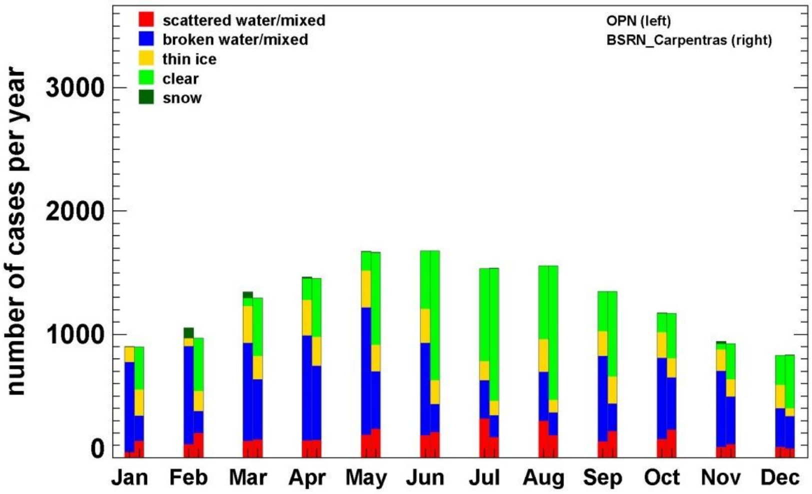
This type of histogram can also be drawn for specific cloud types. In La Réunion Island, the situations of optically thin clouds (high cirrus) can last quite long (several days). The corresponding histogram shows a bulge for the 8 to 12 hours period, which is in adequacy with the local observations saying that this cloudy situation can last all day (the APOLLO clouds analysis is done only for the daytime slots).



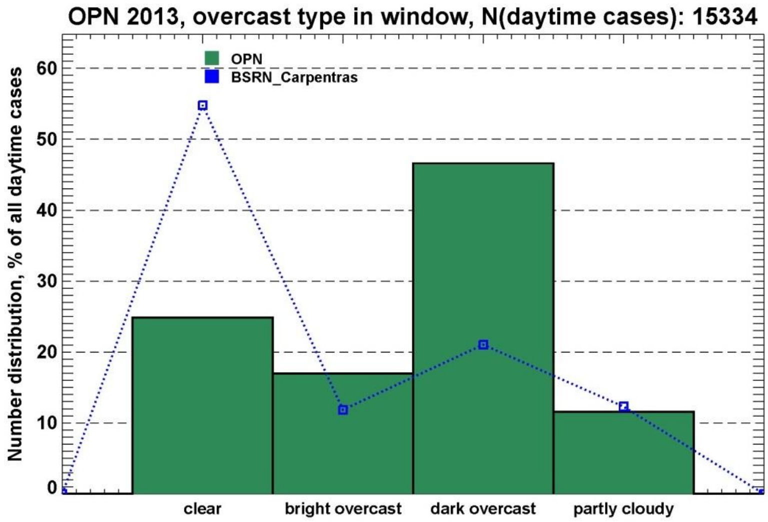
Comparing two locations

This section provides further examples for two locations at the BSRN station location in Carpentras, France and the DLR site Oberpfaffenhofen, Germany, which are compared against each other for the meteorological situation in 2013.

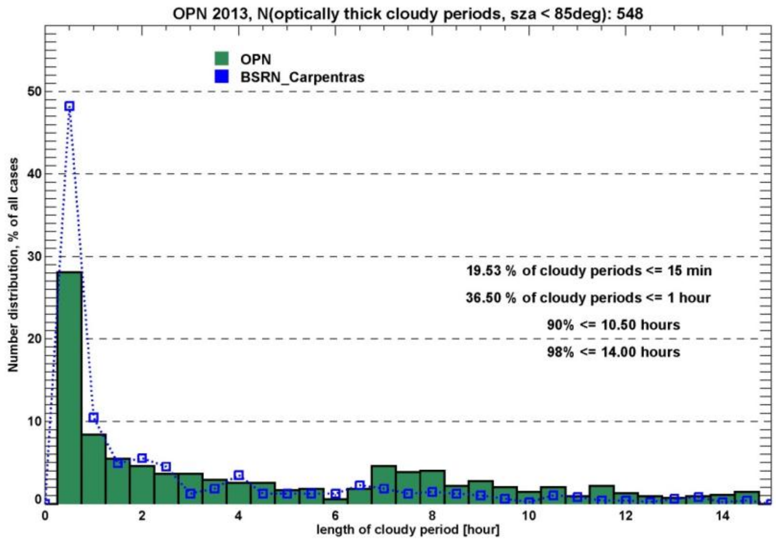
Differences between Southern France and Southern Germany as a function of time of the year can clearly be seen. The number of broken/overcast water and mixed phase clouds is significantly higher in Oberpfaffenhofen in winter, spring and autumn months, while during summer the differences are much smaller – but the number of thin ice cases differs on the other hand especially in August.



For photovoltaics the difference in dark overcast situation occurrence can be seen as well:



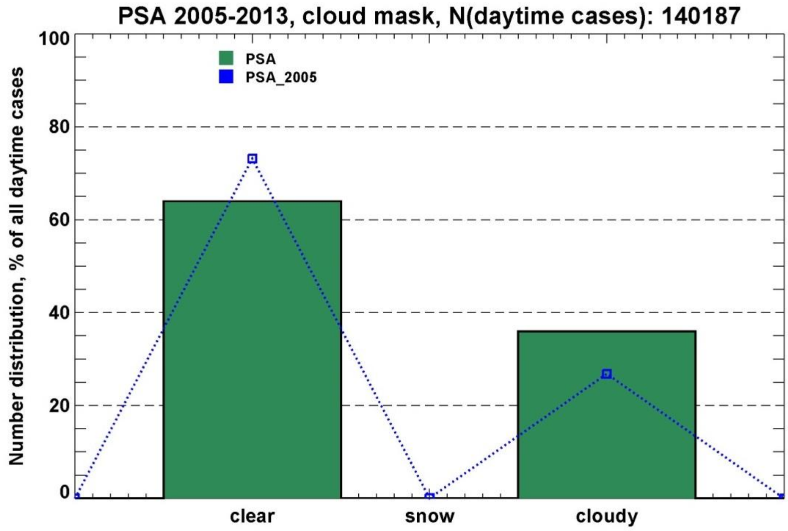
The difference in the typical length of cloudy periods can be seen clearly – in Germany, the number of long cloudy periods for optically thick clouds with 7 or even more hours are much more frequent than in Southern France.



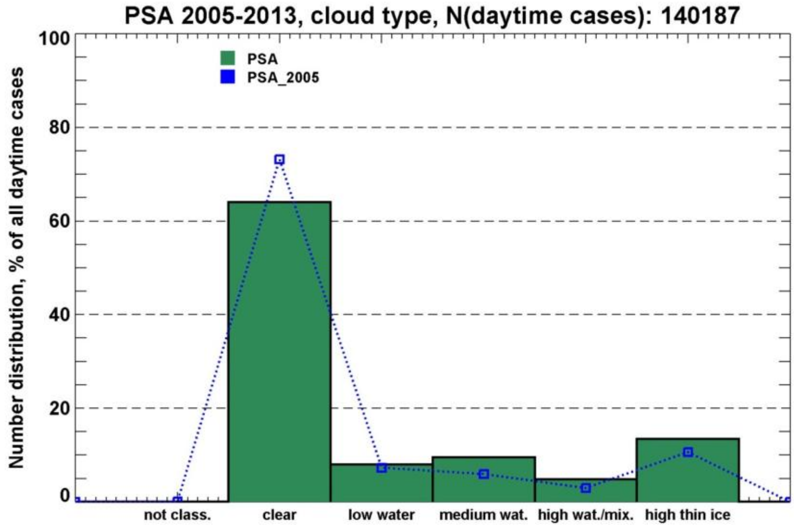
Comparing a single year versus the multi-annual statistics at a single location

This section provides further examples for the location of the Plataforma Solar de Almeria (PSA, Spain). A single year (2005 or 2006) is compared against the long-term statistics based on 2005-2013.

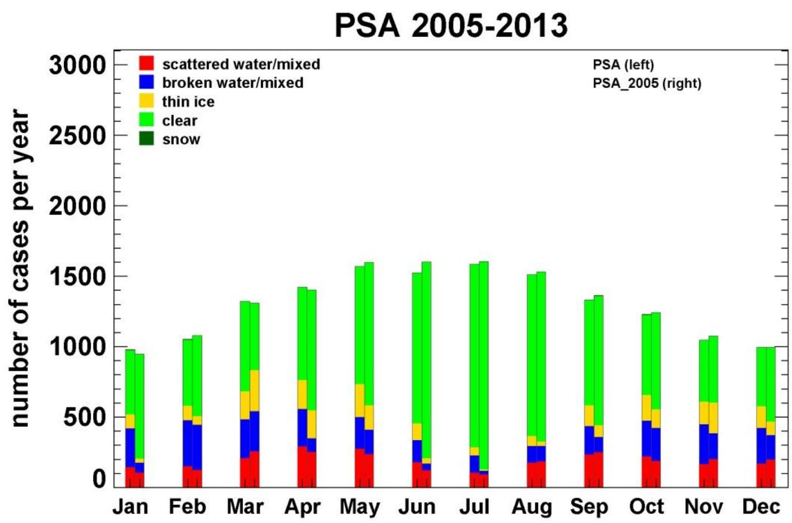
Overall, 2005 has approximately 5% less cloud cases at the PSA. Any yield estimate based on a 2005 ground measurement would overestimate the actual energy yield most probably.



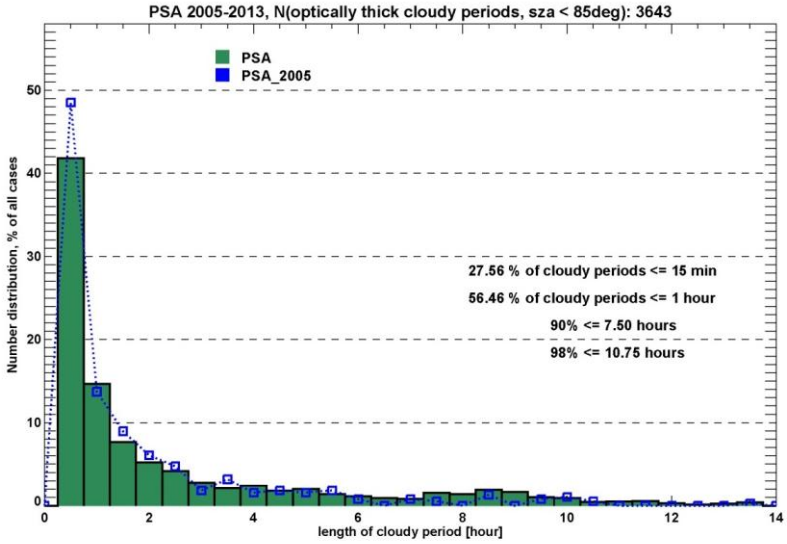
Those 5% less cases are distributed equally on medium height level water clouds and cirrus cases. In case of PV the cirrus cases are less important; depending on the technology (PV or CSP) the risk of overestimation of energy yield based on the 2005-only ground measurements is therefore less.



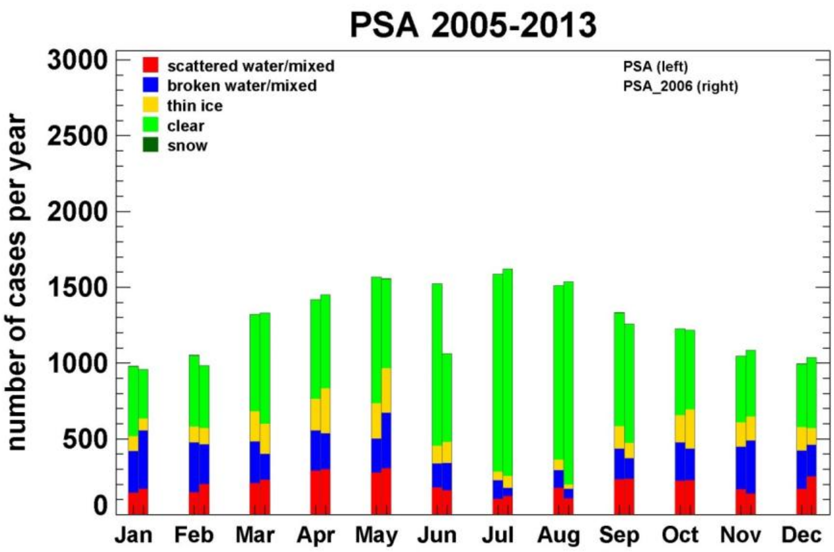
Comparing the differences on a monthly basis show that especially in January, April, June, July and September were clearer than on average, while the situation in March was much more cloudy.



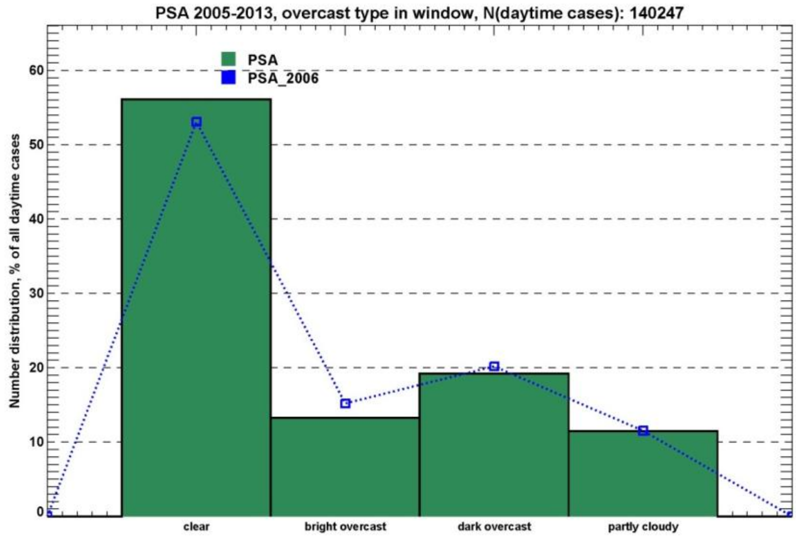
In case a storage system is planned, the nearly missing occurrence of long 7-9 hour long thick cloud durations and the larger occurrence of short 1-2 hour long thick cloud durations is relevant. Any PV storage design should not rely on a 2005 based ground measurements only. For CSP on the other hand the histogram of cloud period lengths is the same for 2005 and 2005-2013 (not shown as a figure). Therefore, depending on the intended solar technology, our findings on the representativeness of the year 2005 with respect to storage design is completely different.



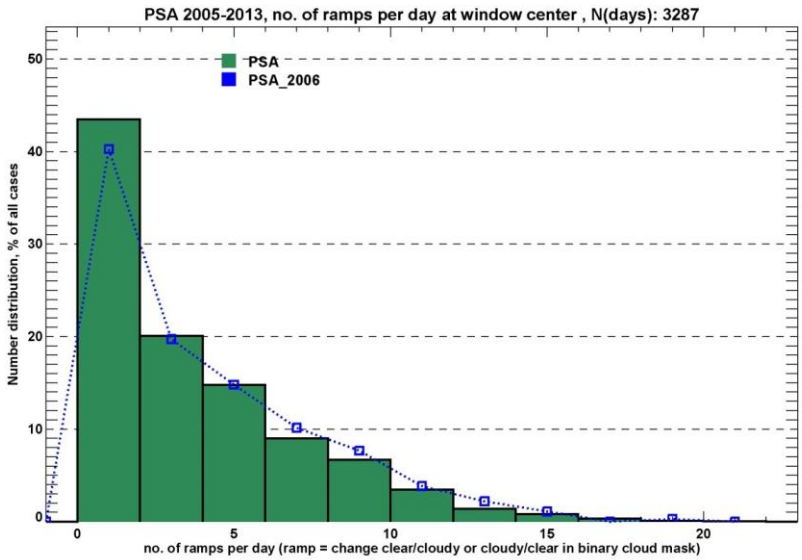
For 2006 on the other hand the number of cloud cases is less than 1 % different from the long-term average. Nevertheless, Pozo et al. (2011) have shown in their Fig. 2 a negative anomaly in GHI and DNI for Jan – Oct 2006 and a close to zero anomaly in Nov and Dec 2006 - compared to the long-term monthly averages. Looking into cloud conditions, we see that January, May, June, and November show clearly more broken/overcast conditions as on average. In April, May, June, October and November, also the number of thin cirrus situations is larger than on average. This analysis takes the neighborhood of the location into account. Overall, 6 months out of 12 show more and another 2 months show a similar number of cloud situations in the region, while the PSA location itself has an average number of cloud mask cases.



The overcast situations in 2006 have been more 'bright' cases than dark overcast cases. In terms of PV energy yield, 2006 can be seen as a more average year as dark overcast cases occur as usual. But the CSP technologies with their sensitivity to DNI are affected – turning the year in terms of DNI into a 'bad' conditions year even if the number of occurrence of clouds at the PSA is similar to the multi-annual average. This example points out that the local neighborhood is important in interpreting and understanding the structures in DNI time series.



This finding is also reflected in the number of cloud/no cloud ramps per day. They are higher in 2006 than on average especially for the high number of ramps per day cases.



Service description

These statistics are available on demand for a specific location as an offline service at the customer demand. Two products will be available.

Product 1 – Single site cloud statistics

This product will deliver in a .pdf report the basic cloud statistics based on the analysis of a long period at a given single site. The report contains the following data:

- cloud mask histogram
- cloud type histogram
- daily and monthly cloud type evolution
- cloud overcast type histogram
- ramps
- cloudy periods duration for all types of clouds

These statistics are complementing a long term analysis of the site irradiation and/or a Typical Meteorological Year data.

Product 2 – Full clouds statistics and site analysis/comparison

This second product will be available in the scope of full site analysis work project defined on a case by case basis with the customer, with the possibility to do multi-site comparisons or inter annual comparisons. In addition to the product 1 statistics, the following data will be added:

- cloud optical depth
- intraday 2D histogram of cloud type evolution
- cloud scatteredness
- cloudy periods duration for specific types of clouds
- multi sites or multi time periods statistics plots

A full report of the site(s) statistics will be delivered. Reports of the comparison of statistics between sites or between periods for a given site will be produced following the customer demands.

References

Armstrong S., Hurley W.G., A new methodology to optimise solar energy extraction under cloudy conditions, Renewable Energy 35 (2010) 780–787

D. Pozo Vazquez, S. Wilbert, C.A. Gueymard, L. Alados-Arboledas, F. J. Santos-Alamillos, M.J. Granados-Munoz, Interannual variability of long term time series of DNI and GHI at PSA, Spain, Solar Paces Conference, 2011

Gesell, G., 1989: An Algorithm for Snow and Ice Detection Using AVHRR Data: An Extension to the APOLLO Software Package. International Journal of Remote Sensing, Vol. 10, Nos. 4 and 5, pp. 897-905

Glas, S., 2014: Analysis of the Relation between Spatial Cloud Patterns in Satellite Images and Variability as seen in High-Resolution Irradiance Time Series by means of their Daily Profile

Categorization, Bachelor thesis, Fakultät Elektrotechnik und Informationstechnik, Hochschule München

Kriebel, K.T., R.W. Saunders and G. Gesell, 1989: Optical Properties of Clouds Derived from Fully Cloudy AVHRR Pixels. Beiträge zur Physik der Atmosphäre, Vol. 62, No. 3, pp. 165-171, August 1989

Kriebel K. T., Gesell G., Kästner M., Mannstein H., The cloud analysis tool APOLLO: Improvements and Validation, Int. J. Rem. Sens., 24, 2389-2408, 2003

Saunders, R.W. and K.T. Kriebel, 1988: An improved method for detecting clear sky and cloudy radiances from AVHRR data. International Journal of Remote Sensing, 9, 123-150

Saunders, R.W., 1988: Cloud top temperature/height: A high resolution imagery product from AVHRR data, Meteorological Magazine, Vol 117, pp 211-221