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Aerosol estimation in the lower planet boundary layer for solar power tower plants' assessment

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Abstract

This study intends to provide information of the aerosol presence of the lowest 150m of the troposphere. The main purpose of it is supporting part of the site assessment process of a Concentrated Solar Power (CSP) plant. It tackles particularly the conditions for the Solar-Tower (ST) technology. The graphical description presented is the result of processing CALIPSO satellite data. For the preliminary results presented here the geographical domain includes North Africa and the Mediterranean. The context and motivation initiate the document. The state of the art, method, and results are described later. The paper ends with the discussion and conclusion remarks where ongoing and planned future research is pointed out.

Keywords: Aerosols; Concentrated Solar Power (CSP); Solar- Tower (ST) plant; extinction; vertical aerosol profiles; dust; CALIPSO; lower Planet Poundary Layer (PBL).

1. Introduction

CSP systems use the thermal capacity of solar radiation. All of them base their operation in one or more reflective surfaces (special mirrors) that focus the sun´s light on a receiver (either a focal line or a single focal point). In this way they produce heat which drives a conventional thermodynamic cycle to yield primarily electricity, although heat can be directly utilized for diverse processes. Some of the systems can use molten salt as a medium to store thermal energy. As a result they can produce energy not only in diurnal cycles but as well during night periods.

Atmospheric constituents play an important role in the variability of the radiation that is collected by the receivers of the above-mentioned solar systems. Chiefly clouds, water

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vapor and aerosols are highly variable in time and space. Thus, the energy yield from CSP systems is sensitive to the influence of these fluctuations.

Of the current offer of technologies in the CSP market, (ST) systems have presumably a higher sensitivity to the variation of water vapor and aerosols in the surrounding atmosphere. This conjecture arise since the distance traveled by the light between the heliostats (mirrors) and the receiver in the tower plant is larger compared to that of the rest of designs. The larger the traveled distance, the higher the potential attenuation of radiation. In a hazy day, in 1km path, attenuation can reach 25% according to (Hanrieder et.al, 2012). If this situation can occur and if the dominant technology in the market is the Parabolic Trough Collector (PTC), why one would be interested on ST? The answer is that despite the possible drawbacks ST technology has some advantages compared to its analogue: it can reach higher temperatures, which allows storage capacity to be longer. It implies an increase of the capacity factor and of the level of the plant´s dispatchability. Additionally when the ST is installed with a large storage capacity, the Levelized Cost of Energy (LCOE) is lower than that of the PTC. Finally, developers expect improvements in operation temperature and efficiency of the system since ST is less mature than PTC.

Fig. 1. CSP technologies. LFC Linear Fresnel Collector. PTC Parabolic Through Collector. DC Dish Collector. ST Solar Tower.

Therefore, there is a need of improvement of many aspects in the site assessment, design and operation stages of the ST plants. Technical site evaluation can be described in 4 steps: site identification, site visit, conceptual design and yield assessment.

Due to technical constraints of the selected device, the present study intends to support only the first step of the technical site evaluation. Site identification requires knowledge of the site conditions including among others meteorological conditions. Although aerosols are a matter of concern, they are not formally evaluated in the current protocols of the feasibility studies. Aerosols need to be described as much as possible not only because of their effect on the optical losses on the light´s trajectory but as well because they affect the mirrors' cleanliness and as a consequence the heliostat efficiency.

We provide a series of geographical maps that allow comparing the difference of the aerosol conditions from place to place. Data source is CALIPSO satellite data.

2. State of the art

In order to acquire information of the aerosol presence in the 150 m above ground it is necessary to have data segmented in the vertical axis. We divided in 4 the current approaches used to obtain aerosol vertical profiles:

- Ground-based measurements: the basic instrument used in this approach is the LIDAR (LIght Detection And Ranging), an active instrument. Although it retrieves segmented vertical data, the current set of ground-based LIDAR stations it is not able to provide homogeneous and global information. It provides as well a limited period of data. Furthermore, the most limiting aspect of LIDAR for the acquisition of information in the lowest layers of the atmosphere is the so called incomplete overlap (Fig. 2.). It occurs because there is a vertical segment in the nearness of the device in which there is no convergence of the field of view of the emitter and that of the receiver. Along this interval the retrievals are not reliable.
- Airborne measurements: the LIDAR is mounted in a nadir-viewing mode aboard an aircraft, solving the incomplete overlap. However this method has several disadvantages. That is, campaigns result expensive, geographical coverage is limited and the period of available data is short.
- Satellite measurements (nowadays only from CALIPSO satellite): similarly, using a nadir-viewing LIDAR, this method overcomes the problem of incomplete overlap. In addition, it offers nearly global coverage. However, it has some weak points. For instance timeframe of data availability is limited. Moreover, the repeat orbital cycle makes it unable for nowcasting and forecasting purposes. The uncertainties and the appropriateness of this method for the description of aerosols in the lowest layer have not been so far well described. Additionally in the nadir-viewing mode the solar background illumination reduces the signal-noise ratio of the backscattered signal. It raises the uncertainty of the device readings.

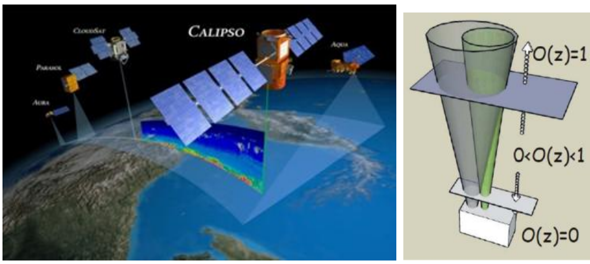

Fig. 2. Left: CALIPSO in the A-train constellation satellite. Right: LIDAR Incomplete overlap (*Source: Navas-Guzmán et. al., 2011*).

- Numerical model simulations: this approach offers a valuable feature that the other methods do not have: time flexibility. Backwards, simulated long time series can be utilized in site assessment purposes. Forwards, simulations would support energy yield estimations in the site assessment and operation stages. Nevertheless numerical models have a high computing demand and a still existing inaccuracy at reproducing complex atmospheric processes.

Overall, all approaches have particular difficulty to register or reproduce suitably the structure of aerosols in the lower part of the troposphere.

3. Method

Due to the interest in having a geographically extended outlook that allows a comparison place to place, CALIPSO satellite was the selected source of data for this study.

CALIPSO has been operating since 2006 and it is part of the A-train satellite constellation. CALIOP is the on board LIDAR that emits at two wavelengths (532 nm and

1064 nm) and that retrieves vertical profiles of aerosols and clouds. It has a repeat cycle of 16 days. For this study level 2 aerosol profile products were used. They have vertical resolution of 60m and horizontal resolution of 333 m. The possible readings given by the flags of the chosen products for each segment (given by the mentioned resolutions) are: invalid, clear air, cloud, aerosol, stratospheric cloud or stratospheric aerosol, surface, subsurface, and no signal. When the feature results as aerosol, the corresponding subtypes given are: clean marine, dust, polluted continental, clean continental, polluted dust, smoke, other or not determined. Similarly the cloud subtype can be: low overcast (either transparent or opaque, transition stratocumulus, low broken cumulus, altocumulus, altostratus, cirrus, and deep convective (opaque).

To create the maps all type of aerosols were considered, since there it is transparent for the solar plant. In order to have a reliable set of data all the profiles with clouds different to cirrus were ignored. It reduced the number of valid profiles. Thus, in search of a trade-off between spatial resolution and number of valid processed profiles, the grid was set to 1° x 1°. Once the cloud filters are checked, the surface has been identified, and the datum is not invalid or not determined the profile is considered. Additionally at least one of the three first segments has to have an extinction coefficient greater than zero. Further details about the assumptions and methods can be found in Mancera (2013).

4. Results

CALIPSO data was processed for the region market out by longitudes between 15°W and 40°E and latitudes between 20°N and 45°N. The reason of the initial geographical selection is that this is the region where large scale projects like DESERTEC are planned. The results are presented as a series of geographical maps. They correspond to the annually averaged values for 2008 of day- and night-time profiles of the following values:

- Total Aerosol Optical Depth AOD (considered from surface to around 8200 m)
- AOD of the layer closest to the surface, from now on referred as 150 m lowest layer(considered between surface and a height that varies from120 to 180 m depending on the terrain´s relief)
- Contribution of aerosols in the lowest 150 m: the portion of total AOD that is in the lowest 150 m
- Density of processed valid data points (for each grid cell).

Speaking of total AOD, it is possible to distinguish higher attenuation due to aerosols in certain regions. Northern Mauritania, Northern Mali, Algeria (mainly south), Turkey, Balkan Peninsula, Tunisia, central Libya, the Nubian Desert in Eastern Sahara and the Red Sea adjoining the North Sudan coasts are the areas with the higher total values of AOD.

The difference of density of data points between day and night (Fig. 3) (more noticeable over land) can be a consequence of the lower signal/noise ratio of the CALIPSO readings during days. This ratio is expected to be even lower over land because the albedo there is higher than that of water bodies. It invites to us to reflect on the appropriateness of the daytime data for our purpose despite the application is related with the diurnal conditions.

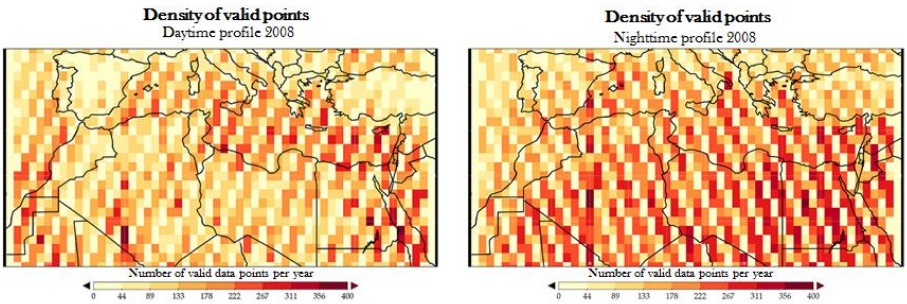

Fig. 3. Left: Density of valid points for daytime 2008. Right: Density of valid points for night-time 2008.

5. Discussion

The qualitative agreement between our results and other estimations of dust in regard to the regions with higher attenuation (Fig. 4) reflects a presumptive dominance of dust in the aerosol counting. It is an expected condition because the analysed region is mostly desert or at least arid. Certain regions like some parts of Turkey, Spain, and the Balkans have a high load of aerosols though they are not known as dust sources. In those cases the origin of aerosols can be explained by other reasons. For example a gravitational settlement of dust particles is expected as they move away from the source during transport processes (Kaskaoutis et al., 2012). The different paths of dust transport (from the African sources across the Atlantic towards America, and across the Mediterranean towards central and east Europe) (Engelstaedter et al., 2006) can enhance the particulate presence over the regions in question. Likewise pollution, volcanic ashes, anthropogenically modified sources, combustion of biomass by anthropogenic activity, and contributions from barren and arid plateaus are counted within the possible aerosol sources.

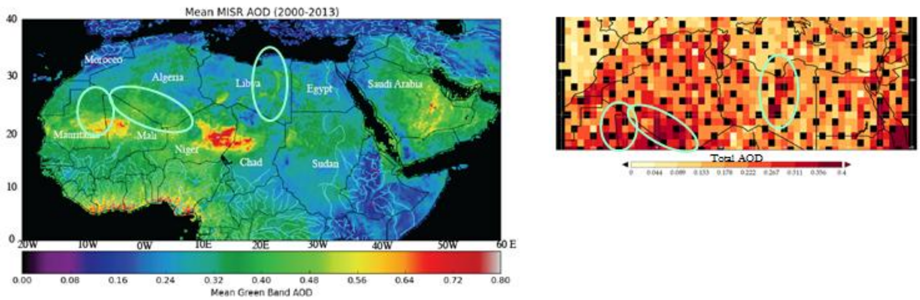

Fig. 4. MISR AOD (Kalashnikova et al.2014) Talk at Dust Conference 2014.

Based on the results of the maps labeled as Total AOD and Contribution of aerosols in the lowest 150 m, we propose a classification of scenarios in 4 cases (Fig. 5). The latter would facilitate the preliminary evaluation of the suitability of conditions for a CSP plant regarding aerosol presence. That is:

- **LoLo** (Low contribution up to150 m - Low total load): the optimum case. Low loaded total column respect to the rest of the region and from the particulate present along it a low concentration is in the lowest part.

- **HiHi** (High contribution up to150 m - High total load): the worst case. The total column is highly loaded by aerosols compared to the rest of the region and a large portion of them is located in the lowest 150 m)
- **LoHi** (Low contribution up to150 m - High total load): the total column is well loaded of aerosols compared to the rest of the region. However the majority of the particulate is not located in the lowest part. Since the whole column is polluted, independent on the location of the particulate, the radiation is expected to be significantly attenuated when it reaches the surface, with which the energy output degrades. This could be the case of a region where the particulates of a sandstorm are travelling far away from the source and remain at higher altitudes.
- **HiLo** (High contribution up to150 m - Low total load): the whole column is relatively clean respect to the region but a large part of the particulate of this column is concentrated in the lowest part. In this case it is possible that the locations are not suitable for a ST plant but instead for other type of CSP technology.

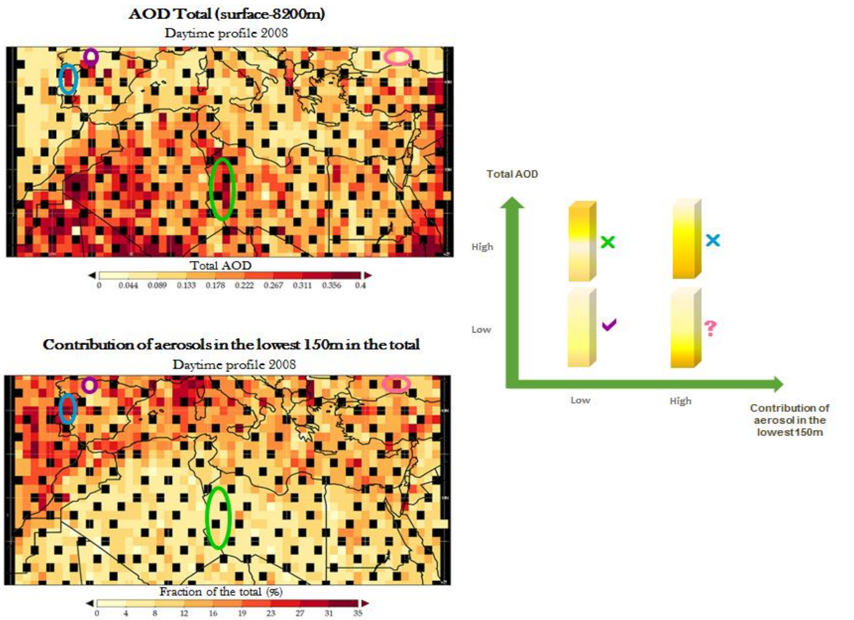

Fig. 5. Left. Up: Total AOD for daytime 2008. Down: Contribution to the total of aerosols in the lowest 150 m for daytime 2008. Right. Proposed categories according to the vertical distributions of aerosols.

As ongoing and future steps of this study we can mention:

- The extension of the geographical domain to global coverage.
- Comparison with numerical models. Namely, MACC model for the global scale and COSMO-MUSCAT for a regional domain. It will provide another reference point for the obtained results. As we introduced at the beginning of this document, we are aware that some restrictions of the satellite technology and the spatial resolution of the maps can limit the application of the satellite approach to the site identification phase. However a better understanding of the vertical distributions of aerosols may result in improvements in the yield assessment since current software tools to do these calculations assume either standard conditions or limited

scenarios (Hanrieder et.al, 2012). An analysis of the comparison of satellite data with numerical model data could provide a new criterion to consider the utilization of models to estimate in advance the energy yield for design and operation.

- Partial validation of satellite and model datasets with airborne and ground-based measurements is planned.

The above-mentioned planned outputs will be supported by the corresponding analysis of sensitivity, variability, error, and uncertainties.

6. Conclusions

In order to estimate the presence of aerosols in the lowest part of the troposphere, we selected a preliminary approach based on CALIPSO satellite data. In this study we have presented geographical maps of the extinction due to aerosols for North Africa and Mediterranean regions. Attenuation is represented by the AOD for both, the total column and the vertical segment of around 150m above the ground. Our objective is providing useful information for the site identification of a CSP plant. A geographical extension of the domain is one of the goals of the ongoing tasks of this work. Technical limitations of the satellite techniques make necessary tackling complementary approaches to support the conclusions of this study. In this case a comparison with models and a partial validation with ground-based and airborne datasets are planned as further steps.

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