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Interactive Comment

Interactive comment on "Evaluating the spatio-temporal performance of sky imager based solar irradiance analysis and forecasts" *by* T. Schmidt et al.

T. Schmidt et al.

t.schmidt@uni-oldenburg.de

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We would like to thank the reviewer for the valuable comments on our article.

First, we would like to respond on the reviewers general comments regarding the underlying measurements used for the evaluation:

We agree, that underlying pyranometer data (photodiode based) has inherent uncertainty and we do not give a special focus on measurement quality. We would like to give some arguments for this decision. First, there is a separate paper (Madhavan et al.) cited in our paper which is focusing on the sensor network. Details on the pyranometer

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calibration, quality analysis and the flagging of the measurements are given. Therefore we decided not to present a separate preliminary analysis. As we only used measurements flagged as "perfect" in our analysis we assure to filter out dramatically bad data (misaligned sensor stations, dirty pyranometer domes). Signal noise will certainly have influence on error metrics, but will be small compared to the error introduced by the image based analysis and forecasting method itself. Moreover, since we use RMSE for forecast error evaluation, the influence of small errors introduced by noisy data is reduced. Shading of pyranometers by obstacles like trees is reduced as we filtered out times when sun is lower than 10° elevations.

In order to emphasize the quality check of the data provider and the quality flagging we modified section 2.2:

"The maintenance as well as cleanliness and tilt control were performed on a∼weekly basis. Based on the maintenance protocol, data is provided with quality flags ("good", "okay, but sometimes spurious", "bad or ignore completely" or "missing or no observations"). Madhavan et al. (2015) give a description of the pyranometer network within the HOPE campaign, details of the hardware, quality flags and an investigation of measurement uncertainties."

We also had to change "perfect" to "good" on p.27012 l.12, as the naming of flags has changed.

Regarding the comment on accuracy criteria:

We agree, the term "accuracy" as the metric for the accuracy of a binary classification is somehow confusing. But "accuracy" is next to "proportion correct (pc)" or "fraction correct (fc)" a correct term describing the proportion of true forecasts among all forecasts (Metz, 1978). It is a simple metric describing how well the methodology can forecasts one of the two states (sunny / cloudy). We added a reference on p.27013 l.8 to the paper of Metz which describes/defines the term accuracy Metz, Charles E. 1978. "Basic Principles of ROC Analysis." Seminars in Nuclear Medicine 8 (4): 283–98.

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doi:10.1016/S0001-2998(78)80014-2.

Regarding the comment on using MAE complementary to RMSE:

We agree, that using MAE complementary to RMSE would have been a possible and also interesting metric. We decided not to use both metrics in order not to overload the paper. We decided for RMSE as it is commonly used in solar energy forecasting because large differences between forecast and observation can lead to urgent problems when aiming at balancing production and consumption of electricity.

In the following, we will respond on the technical comments:

- p. 26998, lines 1-2:

Reviewer Comment (RC): Clouds are not "always" the source of variability for GHI. Aerosols, for example, can be also, in some places, dominant sources of variability. In the site of interest here, it is of course true (but aerosol and water vapor may have some temporal variability pattern: but maybe not spatial pattern for the spatial scales of interest here).

Author Response (AR): We did not want to neglect the influence of aerosol and water vapour variability on GHI variability. In contrast, we wanted to emphasize the important role of clouds, which is the predominant factor if we focus on the temporal and spatial scale we are focusing on with sky imagers. In our methodology we account for changes in the atmospheric turbidity by using near-real time data for the estimation of the non-cloudy and the cloudy state.

Therefore, we modified the first sentence to:

"Clouds are the dominant source of small-scale variability in surface solar radiation and uncertainty in its prediction."

- p. 27000, lines 3-5:

RC: Occlusion of sun is only related to the direct and circumsolar part of the GHI

AR: Correct, point forecasts for the occlusion of the sun on the first hand only predict direct radiation. For an estimation of the diffuse radiation level the cloud patterns in the visible image can be used for a radiative transfer modelling. Another technique is a machine learning based model training a set of image features on the measured diffuse radiation.

- p 27002, lines 13-16

RC: Authors should better explain and discuss (briefly) the choice of this particular clear sky modeling (compared to other more recent clear sky model)

AR: The used clear sky model in this study is also used in internal operational services for pv plant energy yield monitoring and evaluated continuously at more than 100 sites in Germany. See Ineichen et al. (2013) for a recent validation of the model. Moreover, the usage of a more recent and potentially more accurate clear sky model would not affect key results and conclusions. In this study, clear sky irradiance is used for persistence modeling and for deriving the radiation levels from the clear sky index histograms of past measurements. For persistence modeling, the choice of another clear sky model would have no significant impact, as the time window (25 minutes) is rather short and the clear sky trend on these short timescales should be similar for different clear sky models. As long as the histograms "overcast" and "clear" peaks can be detected, the choice of another clear sky model would not change the forecast accuracy or the error metrics, respectively. Moreover, it is used when evaluating accuracy of the binary forecast. Here, the threshold for the classification is based on the clear sky index. Therefore, the choice of another clear sky model could lead to a different distribution of binary (sunny and cloudy) classes. Due to the mentioned arguments for the low impact of the choice of the clear sky model, we decided not to go into more detail when introducing the used clear sky model. However, we added one sentence regarding the models performance:

"The model is also used in internal operational services for pv plant energy yield monitoring and evaluated continuously at more than 100 sites in Germany within our group. For a recent independant validation of the model, see Ineichen (2013)"

References: Ineichen, P.: Long Term Satellite Hourly, Daily and Monthly Global, Beam and Diffuse Irradiance Validation. Interannual Variability Analysis; IEA Report; University of Geneva: Geneva, Switzerland, 2013.

- p. 27004, line 7:

RC: Where does the definition of intensity come from?

AR: We used the definition of "luminance" here, which gives each color (red, blue, green) in the color space a certain weight. In order to make this clear to the reader, we changed the footnote to

"Pixel intensity/luminance I = 0.299 * Red + 0.587 * Green + 0.114 * Blue"

- p. 27004, lines 9-14:

RC: The discussion about a,b and the threshold is too brief. "Empirically determined": ok but what is the criteria? Finally, what are the values for a, b and this threshold?

AR: We agree with the comment and extended this paragraph with a more detailed description of the used parameters. "The values for a=0.1, b=0.0018 and R_{thres}=0.82 that discriminates clouds and sky were determined empirically on a test dataset of 40 images with different sky conditions. They were adjusted with the aim to achieve good results for all possible sky conditions, including in particular thick and dark clouds, semi-transparent cirrus clouds as well as clear sky."

- Section 3.1.2:

RC: References for this extrinsic/intrinsic calibration would be welcome

AR: The intrinsic calibration (lens function, Eq. 2) is based on Scaramuzza et al. 2006 and 2014 (two references are given in the paragraph). The intrinsic calibration is only

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based on camera characteristics and independent from the positioning of the camera itself. What is called "extrinsic" calibration means the orientation of the camera frame to the 3d world. The extrinsic parameters depend only on the position of the camera. This positioning can be described by a 3x3 rotation matrix. As we assumed a horizontally aligned camera (no rotation in x- and y-axis) only the orientation to hemispheric north (z-axis) has been considered. The rotation of the z-axis has been determined by comparing calculated and visible sun position on a clear sky day. As the visible sun position cannot be determined automatically in our case (other groups used a black pixel in the center of the sun which is not available for the camera we used here), we performed a "visual" comparison on a clear sky day. We think there is nothing to cite here.

- Section 3.1.6:

RC: Author should discuss about the choice of a relatively large value of the spatial smoothness

AR: The chosen gaussian filter is used to smooth cloud edges, based on binary cloud masks, leading to sharp gradients or strong flickering in the transition from cloud to sky or vice-versa. The chosen filter is a simplification because it is static and does not account for different optical properties in the transition zone of cloud edges. Here, the chosen filter size lead to the best correspondence of measured and calculated ramps (see Fig.6 for the smoothing effect at cloud edges). A comparison of different filter sizes is not given. Outlook: A more realistic approach would calculate the filter size based on cloud base height and opening angle of the sun.

We added the reference to Fig.6 section 3.1.6:

"The effect of smoothed cloud edges is illustrated in the timeseries of the forecast example in Fig.6."

- p. 27008, lines 20-21:

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RC: authors should briefly describe a summary of the possible improvements for the diffuse

AR: If the surface solar irradiance retrieval is based on a binary cloud mask (like in the given study), global horizontal irradiance calculation can benefit from the knowledge of diffuse and direct radiation levels. From the definition of direct radiation it is obvious, that the binary cloud/shadow mask corresponds more to the spatial distribution of direct irradiance than to global irradiance. Furthermore, if we assume a much lower variability in diffuse irradiance, spatial and temporal homogeneous (constant) diffuse irradiance can be summed on direct irradiance (derived from cloud/shadow mask) to estimate a more accurate global horizontal irradiance. In contrast to the used approach that learns from measurements of past 30 minutes, a near-real time estimation of both components (based for example on image features) may reduce analysis and forecast errors. We modified the last sentences to:

"Despite the adaptation to the situation of past 30 minutes, irradiance levels for clear sky (diffuse + direct irradiance) and cloudy sky (diffuse irradiance only) may deviate from measured values (see Fig.6). A more realistic retrieval can benefit from the estimation of direct and diffuse components, e.g. by considering additional image features with machine learning (Schmidt et al., 2015)."

- p.27010, line 4:

RC: "real changes...": i don't understand the scientific meaninng of this sentence.

AR: Cloud motion vectors (CMVs), derived with optical flow technique, have more variability in speed and direction than the principal movement of a cloud (layer) would have. This is due to the fact, that single CMVs are connected often to cloud edges which not always point/move in the same direction as the whole cloud. Averaged over all CMV, the principal movement is approximated much better. As CMVs are renewed from time to time (here, every 2 minutes), the global average can be discontinuous. As sudden changes in cloud motion are less probable, the temporal averaging would reflect the

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"true" principal movement more realistically. We modified the sentence as following:

"Due to recalculation of CMV positions every 2 minutes, discontinuities in the global CMV may occur. As these do unlikely represent true changes in cloud motion which is rather inert, the last four global vectors are also averaged in time."

- p.27010, line 6-7:

RC: interesting: can we know a little bit more about this

AR: The given sentence explains the approach best. It is clear, that part of the forecast error is due to wrong cloud motion estimation. The uncertainty/variability in cloud motion vectors derived from subsequent images can be used to derive information about forecast uncertainty (e.g. ensembles). Details on methodology will be published if results are finished.

- p.27012, fig.7:

RC: Where are the 50 selected stations among the 99 possible represented in Fig. 7?

AR: The 50 stations have been marked in the figure with a red circle. Moreover, we modified its caption: "Left: statistics of available and evaluated forecast instances at all 99 stations in dependency on the forecast horizon. Right: spatial distribution of available and analysed forecast instances for a forecast horizon of 10 min. Stations with a red circle represent stations with more than 70 % of data available."

- p.27014, eq.12:

RC: Ok for this definition but I don't see the relevancy and the use of V inthis paper, except for the table 1.

AR: The same definition is used for the evaluation of forecast error vs variability in Section 4.3 (or Fig. 13). We reference Eq. 12 on p.27018, l.16

- p.27015, l.18:

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RC: do not need this ref to say that RMSE = sqrt(MBEˆ2 + STDDEVˆ2)

AC: We do agree.

We removed the reference.

Here, we address the typo errors:

- We changed all typo errors according to reviewers suggestions. - We modified line colors for Fig. 10 and 12 in order to discriminate better different cloud classes. - Figure 1 is referenced in p. 27001, l.2 where the data set is introduced.

Please find attached modified figures 7, 10 and 12

Interactive comment on Atmos. Chem. Phys. Discuss., 15, 26997, 2015.

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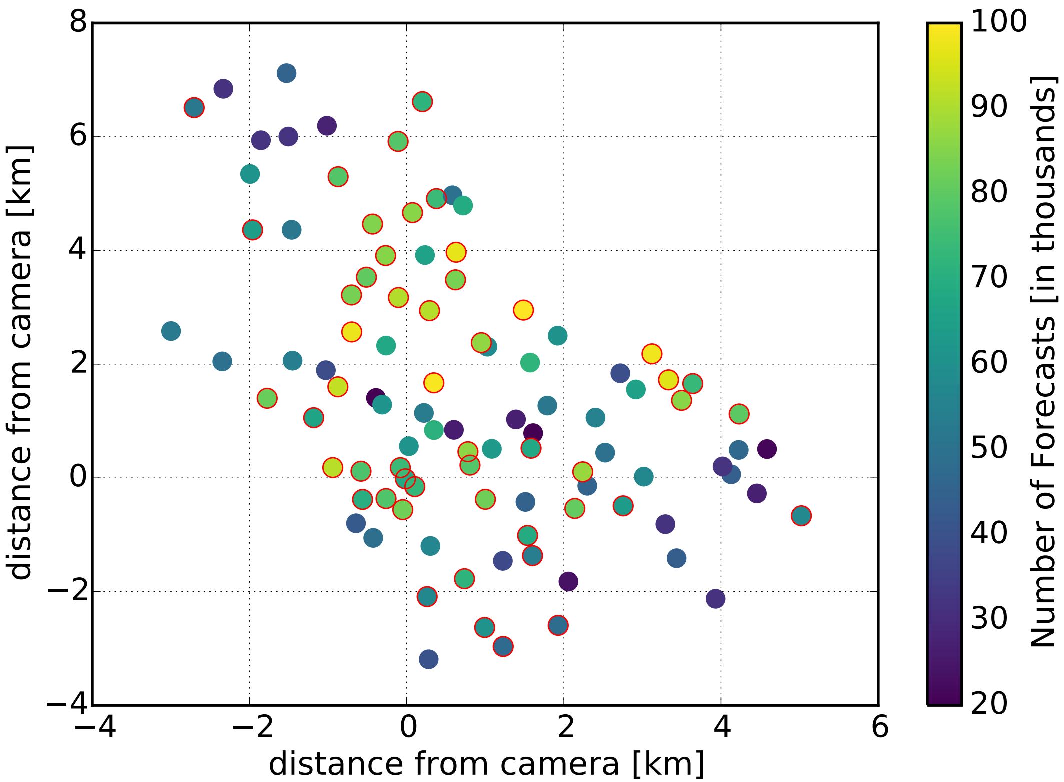

Fig. 1.

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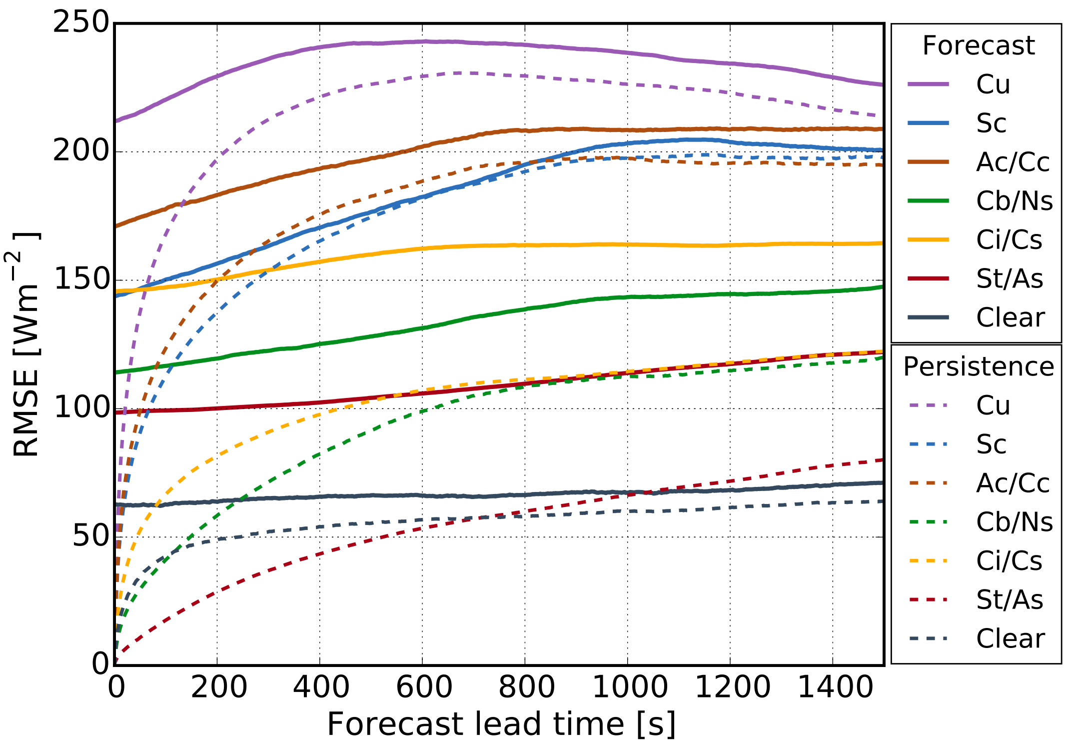

Fig. 2.

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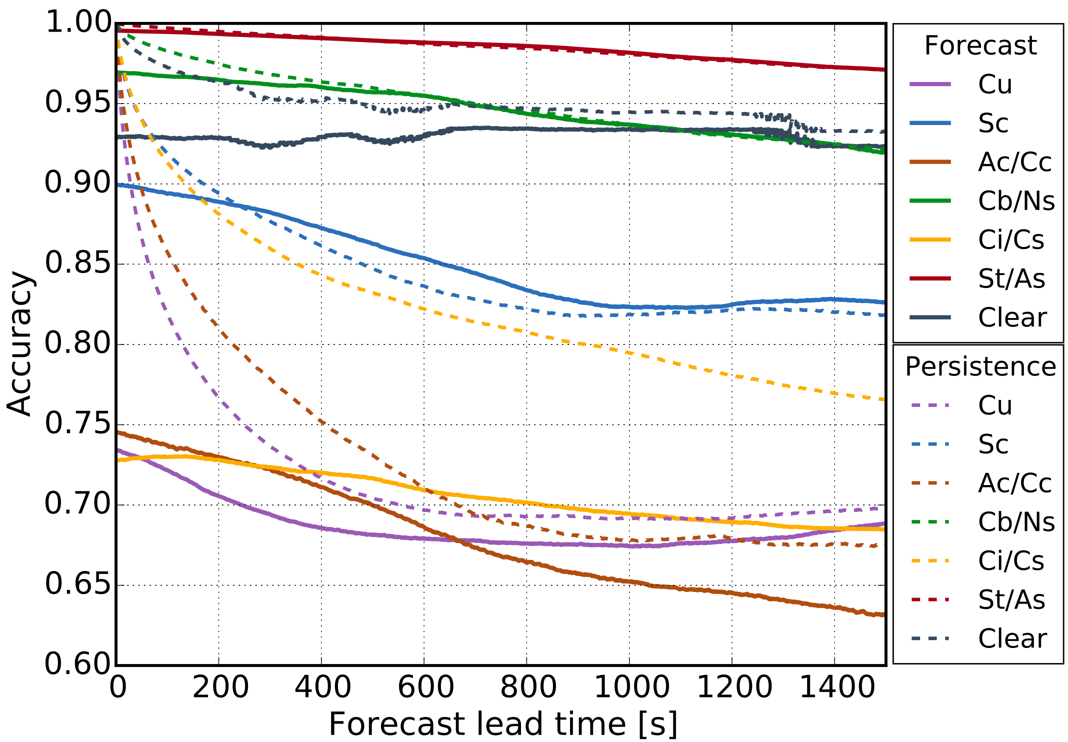

Fig. 3.

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