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Short-range solar radiation forecasts over Sweden

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Abstract. In this article the performance for short-range solar radiation forecasts by the global deterministic and ensemble models from the European Centre for Medium-Range Weather Forecasts (ECMWF) is compared with an ensemble of the regional mesoscale model HARMONIE-AROME used by the national meteorological services in Sweden, Norway and Finland. Note however that only the control members and the ensemble means are included in the comparison. The models resolution differs considerably with 18 km for the ECMWF ensemble, 9 km for the ECMWF deterministic model, and 2.5 km for the HARMONIE-AROME ensemble.

The models share the same radiation code. It turns out that they all underestimate systematically the Direct Normal Irradiance (DNI) for clear-sky conditions. Except for this shortcoming, the HARMONIE-AROME ensemble model shows the best agreement with the distribution of observed Global Horizontal Irradiance (GHI) and DNI values. During mid-day the HARMONIE-AROME ensemble mean performs best. The control member of the HARMONIE-AROME ensemble also scores better than the global deterministic ECMWF model. This is an interesting result since mesoscale models have so far not shown good results when compared to the ECMWF models.

Three days with clear, mixed and cloudy skies are used to illustrate the possible added value of a probabilistic forecast. It is shown that in these cases the mesoscale ensemble could provide decision support to a grid operator in terms of forecasts of both the amount of solar power and its probabilities.

1 Introduction

Solar energy, distributed across the electromagnetic spectrum, warms the Earth, causes weather, and makes life possible. The solar energy is several orders of magnitudes larger than the world's total energy consumption (IEA, 2017). During recent years the strong decrease in the prices of photovoltaic (PV) modules has lead to an increasing interest in harvesting solar energy with PV systems.

Even in high latitude regions like Sweden there is a potential of solar energy contributing to the electricity system. The difference between the available solar energy in Sweden and the Sahara desert is only about a factor of two. The Swedish PV market started out with off-grid systems but since 2007 more grid-connected capacity than off-grid capacity has been installed annually. At the end of 2016 Sweden had about fifteen times more grid-connected than off-grid PV capacity. The total amount of Swedish grid-connected PV increased a 65 % between the years 2015 and 2016 reaching a total of about 200 MWp by the end of 2016 (IEA, 2016).

The increase of PV systems in the electrical grid creates both opportunities and problems. The solar power is variable due to its weather dependence and needs to be forecasted in order to keep the power grid in balance. In this paper short-range (up to 24 h) forecasts of global horizontal (GHI) and direct normal (DNI) solar irradiance from a global and a regional numerical weather prediction (NWP) model are compared. In order to calculate solar radiation on tilted surfaces like solar panels, both the GHI and DNI are needed. The global model used is the Integrated Forecasting System (IFS) from the European Centre for Medium-range Weather Forecasts (ECMWF). The regional model is represented by the non-hydrostatic convection-permitting HARMONIE-AROME model that is developed in a code cooperation with Météo-France and the NWP consortia HIRLAM and ALADIN.

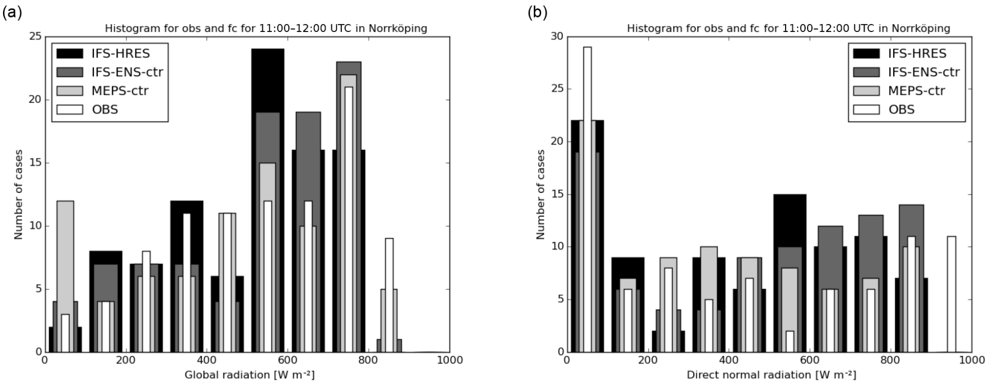

Figure 1. Histograms with modelled forecasted (fc) and measured (obs) GHI (left) and DNI (right) for the hour 11:00–12:00 UTC during April–June 2017.

The use of regional high-resolution NWP models and probabilistic forecasting could be useful in order to support decisions by electricity system operators facing variable renewable energy sources with fast transients in the power grid. However, so far previous studies have shown that the coarser non hydrostatic IFS model outperforms high resolution models when it comes to forecasting solar radiation (Perez et al., 2013). One important reason for this is that higher resolution models suffer from a double penalty where small displacement errors in clouds are counted twice, first where the cloud is missing (but should be) and again where it is present (and should not be). On the other hand, a coarser model will present a smoother cloud cover and agree better with the observations at both locations. This problem with high-resolution forecasts is described, for example, in Mittermaier (2014). This effect might also be the reason behind the degradation for high-resolution forecasts of solar power as examined by Lara-Fanego et al. (2012), where it was concluded that the DNI forecast degrades when the horizontal resolution is chosen too high, ie. finer than about 10 km. Nevertheless, high-resolution NWP can be utilized, especially when the unpredictable components in the forecast can be removed by the use of an ensemble prediction system. This method was demonstrated by using an ensemble of HARMONIE-AROME for wind power in cold climates by Söderman et al. (2017). Here, some case studies will show that regional ensemble models can indeed provide added value to forecasts of solar radiation available for PV power production.

2 Data

This section describes the characteristics of the global and regional model together with the ground observations from the Swedish Meteorological and Hydrological Institute (SMHI) radiation network that was used for the comparison. The comparison uses hourly data from Norrköping (58.58° N, 16.15° E) during the time period April–June 2017.

2.1 Integrated Forecast System (IFS)

The NWP system developed and used at the ECMWF is called Integrated Forecast System (IFS). Since 2007 (cycle 32R2) the IFS model provides both global and direct normal irradiance solar radiation fluxes at the surface. The radiation model is based on the Morcrette radiation scheme from cycle 25R1 (Morcrette et al., 2008) and uses the Rapid Radiative Transfer Model of Mlawer et al. (1997).

In this study data from both the deterministic Atmospheric Model high resolution (HRES) and the Ensemble – Atmospheric Model (ENS) from cycle 41R2 has been used. The IFS-HRES has a horizontal resolution of about 9 km (O1280 grid) and 137 vertical levels while the control and the 50 members of the IFS-ENS have 91 vertical levels and a horizontal resolution of about 18 km (O640 grid). Both models are described in the IFS documentation (ECMWF, 2016).

Operational IFS forecasts started at 00:00 UTC with a length of 24 h and hourly time steps (accumulated values) were extracted from the MARS archive at ECMWF.

2.2 MetCoOp Ensemble Prediction System (MEPS)

In MetCoOp (Meteorological Co-operation on Operational NWP), the meteorological services of Sweden, Norway and Finland run jointly a high-resolution ensemble prediction system, the so-called MetCoOp EPS (MEPS).

MEPS is developed in the framework of the shared Aire Limitée Adaptation Dynamique Developpement InterNational (ALADIN) – High-Resolution Limited-Area Model (HIRLAM) NWP system. This system can be run with different configurations. Here the current cycle (40h1.1) of the so-called HIRLAM-ALADIN Regional Meso-scale Operational NWP In Europe-Application of Research to Operations at Mesoscale (HARMONIE-AROME) is used (Bengtsson et al., 2017). The main components of the ALADIN-HIRLAM NWP system are surface data assimilation, upper-air data assimilation and the forecast model for the forward

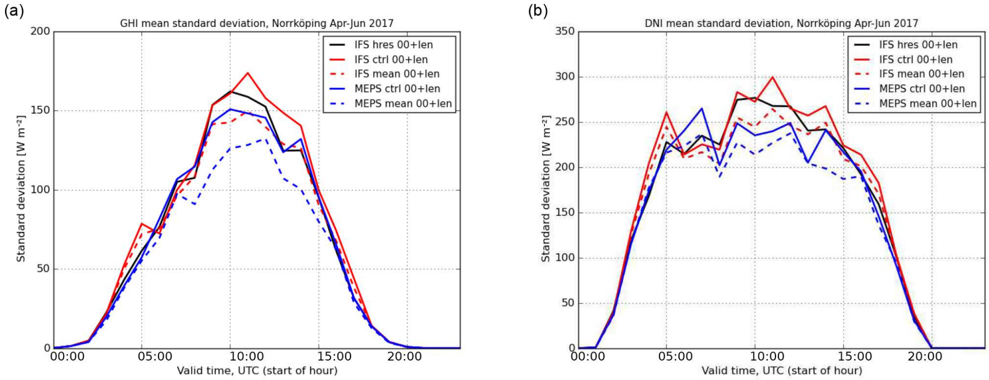

Figure 2. Standard deviation of differences between modelled and measured GHI (left) and DNI (right), Norrköping, April–June 2017.

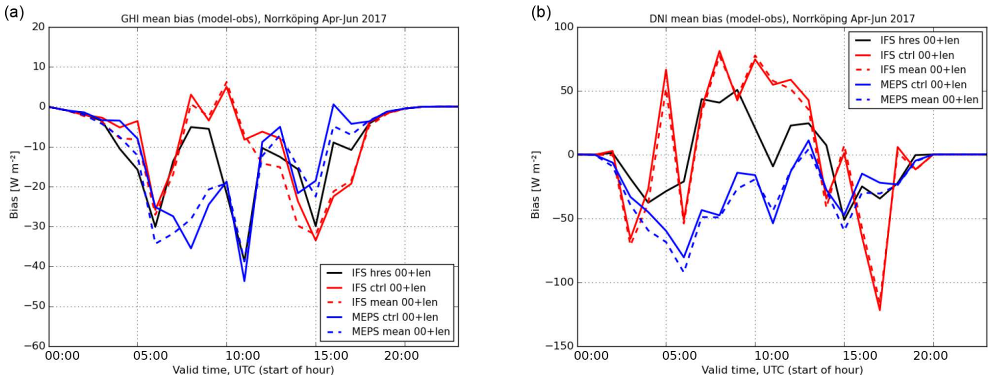

Figure 3. Bias between modelled and measured GHI (left) and DNI (right), Norrköping, April–June 2017.

time integration. Radiation in MEPS is parametrized in the same way as in the IFS model.

The model domain contains 900×960 points with 2.5 km grid spacing and 65 levels covering the Nordic region. MEPS consists of one control plus nine ensemble members. The Scaled-Lagged-Average-Forecast (SLAF) method (García-Moya et al., 2015) is used to produce initial and boundary perturbations from ECMWF deterministic forecasts using a lagging technique.

Operational MEPS forecasts started at 00:00 UTC with a length of 24 h and hourly time steps (accumulated values) were extracted from the operational archive at SMHI.

2.3 Solar radiation measurements

Since 1983 a network of 12 automatic solar radiation stations is operated by SMHI. The stations are located at latitudes between 55.7 and 67.8° N. Among others, global and direct irradiance are measured. The radiation network was modernized in 2006–2007. Unfortunately only three out of the previous 12 stations could be equipped with direct and diffuse measurements in the new network. Descriptions of the network and some measurement results can be found in Carlund (2011).

In the calibrations for the old network hourly reference and field instrument data were used. In the calibrations for the new network 1 min mean values are used and for this study hourly accumulated values was retrieved from the database.

Solar radiation measurements are sensitive and daily cleaning of the sensors is needed along with yearly calibration and rigorous controls of the data quality. In this study focus has been on measurements from the utterly well maintained station at the SMHI premises in Norrköping where direct and diffuse radiation is still measured.

3 Method

Hourly forecasts of GHI and DNI were obtained by taking differences between accumulated forecasts from $00+\text{LL}+1$ and $00+\text{LL}$ where LL is a forecast length between one and 24 h. Hence forecasts for the time intervals 00:00–01:00 UTC,... 23:00–24:00 UTC were obtained. Corresponding hourly accumulated sums of observed GHI and DNI were calculated. Ensemble mean forecasts were produced as an average of the NWP ensemble members for each forecast hour.

Since the management of the power grid is less affected by small errors the root mean squared error or standard devi-

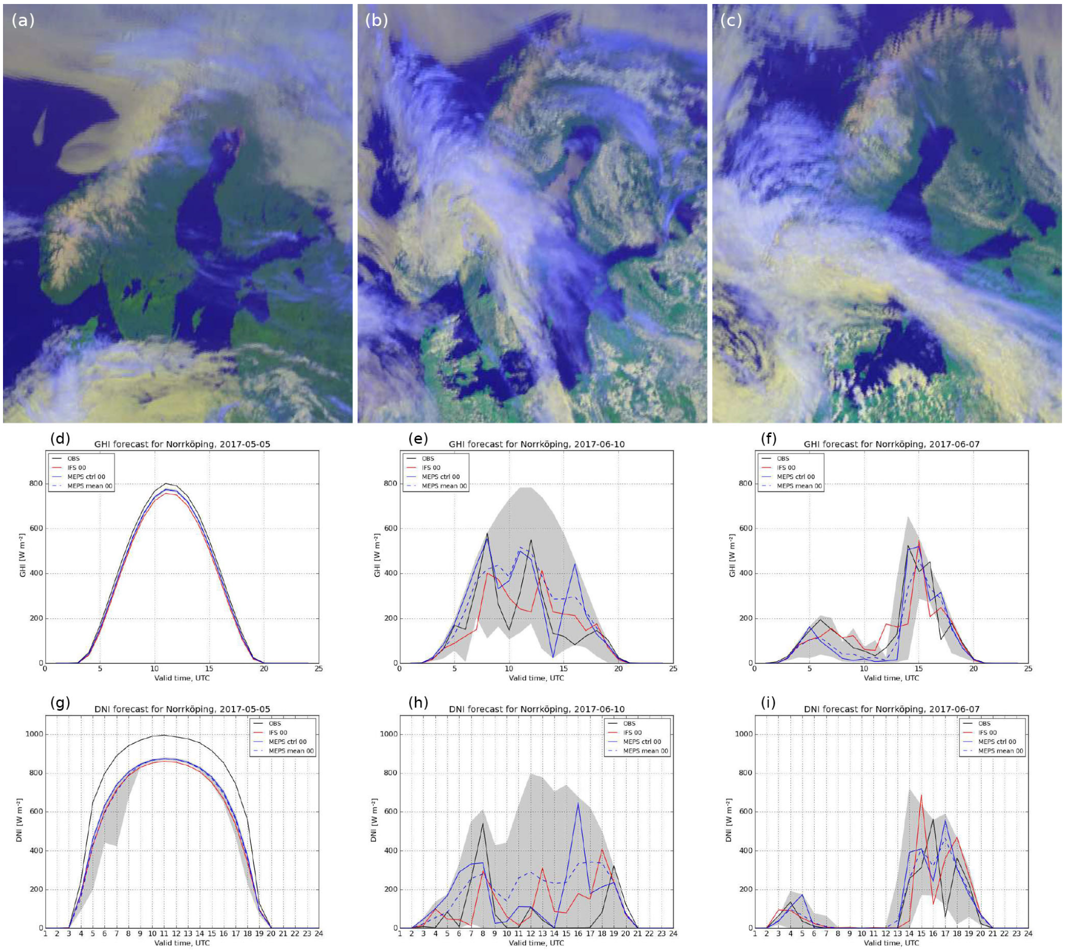

Figure 4. Three cases illustrating forecasts for different cloud conditions: clear **(a)**, mixed **(b)** and overcast **(c)**. Top row: cloud images from Meteosat. Middle row: GHI forecasts. Bottom row: DNI forecasts.

ation are generally regarded as useful error measures. However, as noted earlier, the drawback of such point-by-point distance measures is that it penalizes high-resolution models. Also the bias in terms of the difference between modelled and measured values was investigated.

Histograms of modelled and measured GHI and DNI were calculated in order to determine the match between overall modelled and measured probabilities of given amounts of GHI and DNI. The quality of the ensemble forecast, with respect to how well the distribution of the ensemble members capture the variability of the solar radiation, was only investigated by looking at a number of cases corresponding to different cloud conditions; a clear case, a case with mixed clouds and an overcast case.

4 Results

The histograms for modelled and measured GHI and DNI values for the hour between 11:00–12:00 UTC during the time period April–June 2017 are shown in Fig. 1a and b. For GHI, the MEPS control is in agreement with observations except at the low end where it overestimates the frequency of small GHI values. IFS-HRES and IFS-ENS control tend to underestimate the number of high GHI values, especially IFS-HRES that has almost no cases in the bin with the highest values. During the morning all models overrepresent the number of occations with high values while the pattern is reveresed showing an underrepresentation of high values during the afternoon (not shown).

For DNI all models miss the highest DNI values and also underestimate to some extent the very low values. Again MEPS control show the best agreement with observations for most intervals. For DNI the pattern is very similar for the morning and the afternoon (not shown). The reason why all models underestimate the higher end of the distribution is that there is a systematic underestimation of clear-sky DNI as will be seen when looking at the case with a clear day below.

Figure 2 presents the standard deviation of the difference between modelled and measured GHI (a) and DNI (b) in Norrköping for the time period of interest. During the time of day with the strongest radiation the overall pattern for the GHI standard deviation is that the MEPS ensemble mean performs best with the lowest standard deviation, followed by IFS-ENS mean and MEPS control, then IFS-HRES and finally the IFS-ENS control. The pattern for the DNI standard deviation is almost identical with the exception that MEPS control has lower standard deviation than IFS-ENS control. It should be noted that despite the potential deterioration by the double penalty effect (Mittermaier, 2014), the MEPS control provides lower standard deviation than the deterministic forecasts with IFS-HRES and IFS-ENS control with coarser resolution.

Turning to the bias in Fig. 3, the MEPS control and mean both have a negative bias throughout the day with the lowest values at mid-day. The bias in IFS-HRES and IFS-ENS are similar to each other with a negative bias in the morning and the afternoon but almost no bias at mid-day. One exception is that the IFS-HRES also show a negative bias similar to that of the MEPS at mid-day. That the IFS models and MEPS have similar bias is not so surprising since they use the same radiation scheme which means that the remaining differences are mainly due to the way clouds are treated by the models. Why the IFS-HRES and IFS-ENS model differs is unclear. The difference in resolution is not striking; 18 km compared to 9 km for IFS-HRES. The step between IFS-HRES and MEPS on the 2.5 km grid is greater. However, grid spacing is one thing, the scale of resolved physical process is something else.

Finally, Fig. 4 illustrates the possible added value from using an ensemble solar radiation forecast as decision support for power grid management. The left panel shows a case with a clear day and a certain forecast without any spread in the MEPS ensemble. Here the grid operator could be quite certain that there will be a production of solar power throughout the day. The middle panel illustrates a case where the MEPS system is uncertain whether it will be a clear day or not which could also be useful information for management of the grid. In the right panel there is a case where all MEPS members predict that the sky will be overcast during mid-day, again informaton that could be of value when planning the power production.

Note that the clear case shows that all models tend to underestimate both the GHI and, more severely, the DNI for such situations. This finding is in line with the results from the histogram of the GHI and DNI that was shown in Fig. 1.

5 Conclusions

Forecasting solar radiation can become important already when the amount of solar power only stands for a small part of the energy mix (IEA, 2013). Nowadays NWP models include both GHI and DNI which is necessary to model irradiance on inclined surfaces as is often the case with solar panels. This article compared the performance of the ensemble control and mean from the state-of-the-art global model from ECMWF with those from a version the regional model HARMONIE-AROME used by the national meteorological services in Sweden, Norway and Finland.

Both models share the same radiation code and it turned out that they underestimate the DNI and to some extent also the GHI in clear sky situations. Besides this deficiency, the MEPS model shows a good fit to the distribution of GHI and DNI values. When it comes to errors in terms of standard deviation during the mid-day hours the MEPS ensemble mean performs best (approximately 15 % less standard deviation than IFS-ENS). The MEPS control member even outperforms the IFS HRES which is an interesting result since regional models have not shown good results in previous studies when compared to the IFS from ECMWF (Perez et al., 2013; IEA, 2013; Casado-Rubio et al., 2016; Lorenz et al., 2016). The reason why the result differs between the studies may be due to differences in the climate regions and time periods under consideration.

Three days with different amount of cloud, one clear, one mixed and one cloudy day, were used to illustrate the possible added value of a probabilistic forecast. In these cases the MEPS could provide decision support to a grid operator in terms of forecasts of both the amount of solar power and its probabilities.

Future work will include forecasting solar power to the grid, extending the comparison to include more sites and investigating how well the IFS-ENS and MEPS describe the probabilities of the forecasted solar radiation.

Data availability. Solar radiation data from the SMHI network can be downloaded from the SMHI open data portal; https://opendata-catalog.smhi.se/explore/ (last access: 26 April 2018). However, archived operational data from the ECMWF IFS models and the MetCoOp MEPS model is not publicly available. IFS and MEPS model data used in this study can be obtained from the author.

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