FORECAST ASSESSMENT OF SURFACE SOLAR RADIATION OVER AUSTRALIA

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ABSTRACT

Simulation and forecast of direct solar irradiance (or direct beam) is critical for solar power planning and production. Despite its importance, only recently have numerical weather prediction (NWP) models started to provide this variable as an output and as a consequence the assessment of simulated solar radiation, especially direct beam, is very limited.

The performance of the European Centre for Medium-Range Weather Forecasts NWP model in terms of solar radiation components is presented, with particular focus on the direct beam component. Forecasts out to five days for 2006 at 3-hourly resolution on an 80x80 km2 grid are compared with high quality ground observations at several sites around Australia.

It is found that while monthly averages of global radiation is reasonably well reproduced by this NWP model, differences between model and observations in the direct beam and diffuse radiation components can be as large as 20% or more. Root-mean-square differences and correlation values for the 3-hourly forecast values indicate that in low cloud cover conditions the direct beam is reasonably well forecast. Although forecast performance sensibly decreases as a function of lead time, the correlation for direct beam is relatively large (> 0.7) out to five days. The lack of temporal variability in aerosol concentrations in the NWP model appears to be partially responsible for the mismatch between model and observations in direct beam.

1. INTRODUCTION

Demand for accurate simulation and forecasts of direct solar irradiance (or direct beam) is rapidly increasing since this is a critical input to the planning (simulations) and operations (forecasts) of solar power plants, especially for concentrating solar power. In terms of forecasts, depending on the time horizon required, whether a few hours or a few days ahead, different approaches can be adopted. Because of the unavoidable delay in the production of complex numerical weather predictions (NWP) models run by the major national or regional weather centers, NWP models are often regarded as unsuitable for predictions shorter than about 6 hours. In this range, imaging (e.g. based on images obtained from total sky imagers) and statistical models are normally preferred. However, such a distinction ignores the fact that older NWP output could also be used (e.g. forecasts one day old).

NWP models predict global horizontal irradiance (GHI) resolving physical processes and using columnar radiative transfer models (Morcrette et al., 2007). It should be noted that radiative transfer models are normally computationally very expensive and are therefore only run once every 30–60 minutes – by comparison the dynamical time steps are much shorter (around a few minutes). It may be expected therefore that solar irradiance from NWP may have some shortcomings, especially under highly variable cloud conditions.

Despite the importance of the direct horizontal irradiance (DHI), only recently have NWP models started to provide this variable as an output and as a consequence assessment of this NWP variable is very limited. Very recently, Lara-Fanego et al. (2011) assessed the direct beam produced by a mesoscale model, WRF, for southern Spain for a three-day time horizon (or lead time). They found a strong dependency of the direct beam to both lead time and cloud cover conditions, with model performance considerably deteriorating with increasing lead time and cloud cover.

The performance of the European Centre for Medium-Range Weather Forecasts (ECMWF) NWP model is assessed here against a number of ground station observations in Australia. As in Lara-Fanego et al. (2011) the dependency of solar irradiance to lead time and cloud cover is investigated. The role of the lack of temporal variations in aerosols in the ECMWF NWP is also discussed. Sections 2 and 3 present the data used and the methodology adopted in analyzing the data. Monthly means, correlation and root-mean-square differences as function of both lead time and (proxy) cloud cover are presented in sections 4 and 5. A discussion about the role of aerosol is presented in section 6, and a summary is given in section 7.

2. GROUND OBSERVATIONS AND MODEL DATA

Ground station observations collected by the Australian Bureau of Meteorology (henceforth, the Bureau) are used in this study to assess the performance of the solar radiation produced by the ECMWF model. The Bureau has maintained a national network
of fourteen stations for monitoring global, direct and diffuse solar exposure for most of the first decade of the XXI century (station locations are shown in Figure 1). These stations adhere to the majority of the international Global Climate Observing System (GCOS) Baseline Surface Radiation Network (BSRN) monitoring protocols. Since the temporal coverage of the Bureau monitoring stations is uneven, the analysis in this work focuses on the year 2006. However, even for a well sampled year like 2006 several gaps remain (see temporal coverage in Figure 1).

Measurements are made at the BSRN-specified frequency of 1 Hz and stored as 1-minute statistics (mean, maximum, minimum, standard deviation). However, only 30-minute averages are currently available to the research community. In practice this does not present a limitation in our case since, as described below, the model output has a temporal resolution of three hours. In principle any one of the three quantities of direct, diffuse and global irradiance can be calculated from the other two. The closure provided by measuring all three enhances quality control. The redundancy also improves measurement continuity in periods when one of the measurements fails. However it should be noted that the global irradiance as measured by the unshaded pyranometer has a larger uncertainty than that derived by the summation of the direct and diffuse irradiance components.

The ECMWF model is a world-leading global forecast model used for NWPs over a lead time of many days. The current operational ECMWF model contains the McRad radiation model (Morcrette et al., 2007). The shortwave portion of McRad is based on the rapid radiative transfer model (Mlawer and Clough, 1997). Constituents accounted for in McRad are water vapor, carbon dioxide, ozone, methane, nitrous oxide, aerosols, and various chlorofluorocarbons. Albedo and optical depth are parameterized primarily from the liquid water path and effective droplet radius (Slingo, 1989). From the radiative properties, a two-stream adding method is used to solve the radiative model at each level, resulting in the surface GHI. The ECMWF model spatial resolution used here is about 80 by 80 km2, and the temporal resolution is 3 hours, with forecasts started at 00 UTC with a 5-day lead time. Relevant model output is the GHI and the DHI. The diffuse component is obtained as the difference of the two.

The aerosol optical depth (AOD) data has been obtained from the AErosol RObotic NETwork (AERONET) website (http://aeronet.gsfc.nasa.gov). Level 2 cloud-screened and quality-assured data are used for our analysis. Also, although the three spectral “bands” 500, 870, 1020 nm were assessed, only results from the 500nm are discussed here since, wherever the three (or two) are available for the same site, they have a similar signature in terms of annual cycle, the main feature we are considering. Further, only the Adelaide station is presented in this paper because it is the only one essentially co-located with the solar irradiance observations. All aerosols records are however affected by marked gaps, which limit the computations of their monthly means.

3. METHODOLOGY

As a general approach, we impose gaps to model data whenever there is a gap in any of three components of the solar irradiance observations, at each of the 3-hourly intervals. Including gaps for any of the three components at once might considerably reduce the availability of observations for our analysis, but we noticed that monthly means can markedly vary depending on whether only the gaps in the matching components are considered (e.g. model GHI versus observed GHI) as opposed to when all three at once are considered. Daily averages are computed only when no gaps in the 3-hourly data are present in a (UTC-based) day. At least 20 days in a month are required in order to compute monthly means. The nearest model grid point is taken as representative of the ground station. No attempt is made to account for the representativeness error due to the fact that the model data represent an average value over an area of ca. 1,600 km2 whereas the ground station observation essentially samples a point within that area. In spite of this, the agreement for GHI is extraordinarily good as the ensuing results show. Even considering a year with a good coverage like 2006, several data gaps exist. According to our conventions, six stations have 9 complete months: Adelaide, Broome, Cape Grim, Melbourne, Rockhampton and Wagga Wagga (see filled squares and circles in Figure 1).

AOD data tend to be very patchy, and as such only up to a few monthly mean values are available for each station. Further, of the six sites available – Adelaide, Birdsville, Canberra, Merredin, Milyering and Tinga Tingana – only one of them, Adelaide, is co-located with a solar radiation station. As a consequence, only results for Adelaide are presented.

As indicated in the introduction, solar radiation simulated by models has a strong dependency on the amount of cloud cover. In particular, solar radiation in the absence of clouds (or “clear sky” condition) is generally easier to simulate than in cloudy conditions, as proper representation of clouds is problematic. For this reason, assessment of solar radiation is often assessed separately for clear sky and cloudy conditions. Because cloud cover corresponding to the observed solar radiation is not available for the stations considered in this work, a surrogate (or proxy) for cloud cover is considered instead. Such proxy is defined as the fraction between the diffuse irradiance component and GHI:

\[ CCp = \frac{\text{Diffuse}}{\text{GHI}} = \frac{\text{DHI}}{\text{GHI}} = 1 - \frac{\text{DHI}}{\text{GHI}} \]  \[1 \]

where CCp stands for cloud cover proxy. The advantage of using this proxy is that the same quantity can be computed for the observations and the model data. Thus, although it may not provide a satisfactory fit with the actual cloud cover, this proxy can be computed in a consistent way for the model and observations. Moreover, it targets the quantity we are interested in, namely the fraction of DHI (or alternatively diffuse) to GHI.
4. TEMPORAL ASSESSMENT OF MODELLED GLOBAL, DIRECT AND DIFFUSE SOLAR IRRADIANCE

We begin by assessing the annual cycle of the three components of solar irradiance as given by their monthly means. We compare four ground stations with their nearest model grid points: Broome (a coastal location in the North West), Rockhampton (a coastal location in the North East), Adelaide (a coastal location in the South), and Wagga Wagga (an inland/continental location in the South East). Figure 2 indicates that the modeled GHI is in close agreement with the observations for all four sites. The model GHI is within the observed GHI error bars for all but the summer months and May in Adelaide, and June in Broome (note that no attempt was made to estimate the uncertainty in the model data). In relative terms, however, the monthly relative biases are normally only a few percent, with Adelaide showing the larger relative errors, as shown by the black bars in Figure 3. Such a good performance can be considered a remarkable result, considering the representativeness errors of the model data mentioned above.

The agreement is less striking in the case of DHI. The model tends to overestimate DHI for all four sites except for Broome in the winter months when the modelled DHI is instead underestimated. The over-estimation in the DHI is generally accompanied by an under-estimation in the diffuse component (as a consequence of the relatively small errors in GHI). Given the smaller magnitude of DHI and its larger absolute error compared to GHI, the relative error of DHI is considerably larger than GHI and often larger than 10% (black bars in Figure 4). Note that the abnormally high relative error for Adelaide in May 2006, which reaches almost 60%, is due to a combination of low absolute climatological value (being late autumn) and what looks like an unseasonably low DHI measurement. A close examination of the measurement for this location and month has been carried out, but no suspicious behaviour could be detected in the observations.

The characteristics of the error in GHI and DHI are further investigated by assessing the evolution of the error as a function of lead time. The error for both GHI and DHI tend to become less positive with lead time. Thus, regardless of their value at lead time zero, the error in subsequent lead times tend to become less positive if it is positive at lead time 0, or more negative if it is negative at lead time 0. The reason for such a trend is not immediately apparent and warrants further investigation, for instance by looking at the divergence and curl of the wind field around the analysed stations.

5. STATISTICS FOR THE ADELAIDE SITE

In the remaining of the paper, the Adelaide station is analysed more closely due to its better observation coverage (12 full months, as for Rockhampton) and the availability of a co-located aerosol observation record (not available for Rockhampton).

Summary statistics for the Adelaide station for all three solar irradiance components in terms of correlation and root-mean-square difference (RMSD) as a function of lead time are presented in Figure 5. The first thing to note is that the correlation for GHI is the highest of the three components, followed by DHI (Figure 5 right hand side). Aside for the hours around dawn and dusk for which the correlation is at its worse for all three components, the correlation for GHI is larger than 0.8, a notable value, out to five days, with only a slow decline as a function of lead time. The central part of the day has however a systematically slightly smaller correlation than the mid morning and mid afternoon, perhaps indicating some issues with the tracking of the diurnal (convective) cycle. Although with smaller values, the correlation for DHI behaves in a very similar way to that for GHI, the main difference being the somewhat faster rate of decline as a function of lead time. While the behaviour of the correlation for the diffuse component is generally similar to that of the other two components, the correlation values are markedly inferior for the central part of the day – being less than 0.6 even at lead 0 – again possibly reflecting some issues with convective processes.

The RMSD for the three components clearly bear the signature of the diurnal cycle, with larger values in the central part of the day (Figure 5 left hand side). It is perhaps surprising that the RMSD for the DHI is considerably larger than that for GHI (around 30% or more) even if the DHI is on average about 30% smaller (cf Figure 2). As with the correlation, the RMSD for the DHI increases more sensibly than that for GHI as a function of lead time. The RMSD for the diffuse component is half or less than that for DHI, in line with their mean absolute magnitudes (cf Figure 2).

5.1 Direct solar irradiance dependency on cloud cover

In order to interpret the above summary statistics for the DHI in more detail, the dependency of the correlation and RMSD with respect to the proxy cloud cover (eq. 1) is also investigated. Four CCp ranges are considered: <0.25, 0.25–0.6, 0.6–0.9, >0.9. In particular, the first range (<0.25) essentially targets the (near-)clear-sky conditions. It is apparent that the correlation for this range is larger than for the other three ranges (Figure 6, right hand side). Correlations are consistently larger than 0.7 out to 3 days for this range, with values slightly degrading for days 4 and 5. The decrease in correlations is also apparent in the direction of increasing ‘cloud cover’: while correlation values larger than 0.7 can be seen for the mid morning and mid afternoon on the second range (0.25–0.6), correlations markedly reduce for larger ‘cloud cover’ situations. Indeed, for the largest CCp range (>0.9) correlation values are always lower than 0.5.

The analogous plot for RMSD (Figure 6, left hand side) depicts a similar picture to that for the correlation, with the first CCp range showing smaller errors, at least out to 2 days. While the worsening as a function of lead time is apparent, the increase in error with increasing CCp is less obvious for the simple reason that for lower CCp the absolute magnitude of DHI is larger than
that at higher CC and therefore one can also expect larger RMSDs. Note that the upper bound on the colour scale, 150 W m⁻², does not allow to easily differentiate between the severity of large errors: such a threshold however does not impair the interpretation of this statistic, which is essentially pointing to important errors that need to be addressed in DHI.

6. AEROSOL IMPACT ON DIRECT SOLAR IRRADIANCE

Like with similar models, the ECMWF NWP model utilises climatological values for their aerosol optical depths. Also, given the scarcity of aerosol observations, such climatologies may not entirely representative of the actual seasonal aerosol variations in less observed places. With the view to assess whether deficiencies in direct solar irradiance may be attributable to the lack of a proper aerosol representation in the model, the monthly solar irradiance bias is plotted together with the aerosol optical depth (at 500 nm) for Adelaide for the available full months (Figure 7). Although the aerosol record is shorter than that of the solar irradiance, the aerosol appears to be correlated with the bias in DHI. In particular, accounting for a positive anomaly in aerosol loading (as in Figure 7) within the solar radiation scheme of the NWP should lead to a reduction in the DHI and, as a consequence, a reduction in the DHI (positive) error. Such a correction would reflect positively also on the GHI. A simple scheme that accounts for such a variability in aerosol loading is being devised as part of a follow-on study.

7. SUMMARY

The radiation components of the ECMWF Numerical Weather Prediction (NWP) model have been assessed using Australian ground station irradiance observations and the Adelaide aerosol optical depth record. The year 2006 was chosen because of its relatively good coverage in ground observations. It was found that the global horizontal irradiance (GHI) is reasonably well simulated by this NWP model for the four best observed stations – Adelaide, Broome, Rockhampton and Wagga Wagga – despite the considerable representativeness error (the model has a spatial resolution of 80x80 Km²). However, the direct horizontal irradiance (DHI, or direct beam) is generally considerably over-estimated. Its relative month-to-month errors often exceed 10%. A closer analysis for the Adelaide station indicated that correlation values for DHI are above 0.7 out to day 5, with a slow degradation with lead time. As expected, correlations were found to be larger for low cloud cover conditions, by using a cloud cover proxy. There is an evident deterioration of this statistic with increasing cloud cover. It was noted that aerosols may also account for part of the errors in DHI. Based on these results, there seems to be a general consistency across Australian sites. A closer investigation into the physical processes which determine the bias in the direct beam is needed to understand better the causes of the errors in DHI. Note however that the ECMWF NWP model is continually improving – some of these shortcomings may be alleviated in more recent versions.

6. REFERENCES

Fig. 1 – Map showing the location of the solar irradiance ground stations operated by the Bureau of Meteorology and the data availability (as indicated in the legend) for 2006.

Fig. 2 – Monthly averages of the three components of solar irradiance (global, direct and diffuse) for both observations (with error bars) and ECMWF model for the four stations with the larger data availability for 2006.
Fig. 3 – Relative difference of monthly averages between ECMWF model and observations for global solar irradiance for the four stations with the larger data availability for 2006.
Fig. 4 – As in Figure 3 but for direct solar irradiance.

Fig. 5 – Root-mean-square difference (RMSD) (left) and correlation (right) as a function of forecast lead time for the global (solid line), direct (dashed) and diffuse (dotted) solar components for Adelaide.
Fig. 6 – Root-mean-square difference (left) and correlation (right) as a function of forecast lead time (x-axis) and proxy cloud cover, CC$_{p}$ (y-axis) for the direct beam for Adelaide.

Fig. 7 – Difference of monthly averages between ECMWF model and observations the three components of solar irradiance for the Adelaide station for 2006. The aerosol optical depth (expressed as an anomaly, and multiplied by 1000) at 500nm is also shown for the months in which it is available.