Investigation on the use of NCEP/NCAR, MERRA and NCEP/CFSR reanalysis data in wind resource analysis

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Abstract:

This study aims to investigate the use of different reanalysis datasets in energy production estimates. Wind data from three distinct datasets are analyzed for the territory of Sweden. These are the NCEP/NCAR, the MERRA and the NCEP/CFSR reanalysis datasets. NCEP/NCAR has been commonly used in wind resource analysis during the last decade, while MERRA and NCEP/CFSR were recently released.

The higher spatial and temporal resolutions of MERRA and NCEP/CFSR reanalysis data allow a better representation of the local wind climate. An average improvement of 16% in correlation coefficient with local wind measurements is obtained for MERRA and 15% for NCEP/CFSR when compared to NCEP/NCAR.

Although the three reanalysis datasets appear to be fairly consistent in space, the temporal consistency of some grid data is rather poor. Wind speed data from some NCEP/NCAR and NCEP/CFSR grid points show strong upward long-term trends for the period of 1980-2009. MERRA wind speed data present a high temporal consistency shown by the typically weak downward long-term trends. A case study is presented where the use of inconsistent reanalysis wind data is shown to infer an error of 14% in the energy production estimate, which is highly significant.

The use of MERRA and NCEP/CFSR reanalysis wind data represents a relevant improvement in accuracy for energy production estimates. However, the choice of the most appropriate grid data and the evaluation of the associated uncertainty should be carefully analyzed for each specific case.

Keywords: reanalysis data, local wind measurements, correlation analysis, long-term trend, MCP

1 Introduction

Atmospheric reanalysis data consists on the synthesis of worldwide observational data by an atmospheric model into a regional or global three-dimensional grid. Reanalysis data covers a long time interval back in time and might therefore be used together with local wind measurements to predict the future wind climate (measure-correlate-predict, MCP) at sites potentially suitable to wind power development.

The first generation of reanalysis data was produced in the mid-1990s by the National Centers for Environmental Prediction (NCEP)/ National Center for Atmospheric Research (NCAR). NCEP/NCAR has been the only global reanalysis dataset publicly available for commercial uses since then and it has been intensively used in wind resource analysis. Detailed information on this reanalysis dataset is presented in Kalnay et al. [1].

Three other global reanalysis datasets have been developed by the European Centre for Medium Range Weather Forecasts (ECMRWF). These are the ERA-40 released in 2004 and covering the period 1957-2002 [2], ERA-15 with data for the period 1979-1993 [3] and ERA-Interim released in 2009 and covering the period 1989 to present [4]. The ERA reanalysis datasets are freely available only for research purposes, not commercial.

At the end of 2009 a new reanalysis dataset named MERRA (Modern Era Retrospective-analysis for Research and Applications) was published by NASA's Global Modeling and Assimilation Office and short time after NCEP released the Climate Forecast System Reanalysis (CFSR) dataset. Both MERRA and NCEP/CFSR datasets are publicly available on-line. A complete description of the MERRA and NCEP/CFSR datasets may be found in Lucchesi [5] and Saha et al. [6], respectively. A list of other reanalysis datasets underway or currently available is presented by Trenberth [7].

The increasing variety of reanalysis datasets creates a dilemma that the majority of the wind resource analysts have to face up to. Which reanalysis dataset should be used as long-term reference for MCP calculations?

The main goal of this study is the investigation on the applicability of the NCEP/NCAR, MERRA and NCEP/CFSR reanalysis wind data as long-term references in MCP analysis. Only grid data covering the territory of Sweden are analyzed in this study.

2 Methodology and Results

Table 1 summarizes the main properties of the reanalysis data analyzed in this study.

Reanalysis dataset	Institution	Vintage	Time interval available	Horizontal resolution (^{o}lat x ^{o}lon)	Vertical level	Temporal resolution (h)
NCEP/NCAR	NCEP	1995	1948 – present (Monthly releases; 1 week delay)	2.5 x 2.5	0.995 sigma level	6 (instan-taneous)
MERRA	NASA	2009	1979 – present (Monthly releases; 1.5 months delay)	1/2 x 2/3	50 m single-level	1 (time averaged)
NCEP/CFSR	NCEP	2009	1979 - Dec 2009 (planned to be available on real time)	1/2 x 1/2	0.995 sigma level	1 (instan-taneous)

Table 1: Summary of the main properties of the reanalysis data used in this study. The 0.995 sigma level corresponds to a level of 99.5% of the surface pressure, that is equivalent to approximately 42 m a.g.l. (above ground level) for standard atmospheric conditions.

The fields U and V components of the wind velocity of each dataset were downloaded for all the grid points covering the Swedish territory and used to compute the corresponding wind speed and wind direction. Furthermore, wind measurements from 25 measurement masts (14 met masts and 11 co-locations on telecommunication masts) have also been used in this investigation. The masts are distributed rather uniformly over Sweden. The wind measurements have good accuracy and have been cleaned for erroneous data.

2.1 Correlation analysis between local wind measurements and reanalysis wind data

Correlation analysis between the wind speed measurements from each mast and the nearest NCEP/NCAR, MERRA and NCEP/CFSR grid points were performed. All measured and reanalysis data recorded between the first mast measurement and 2009-12-31 23:59 UT were considered. Outliers were discarded when a mast measurement differs more than two standard deviations from the remaining dataset in the reanalysis wind speed bin. The correlation coefficient (R) of the resulting linear regression fit is used to quantify and compare the strength of the relationship between the mast measurements and the different reanalysis datasets. The results obtained are presented in Table 2. Note that the R-values presented in this table result from the direct application of a linear regression fit to the relation between wind speed measurements and reanalysis wind speed data at maximum possible sampling resolution. No averaging is applied neither on the wind speed measurements nor on the reanalysis wind data. The two last columns show the improvement in R-value using MERRA and NCEP/CFSR relative to the results obtained using NCEP/NCAR data.

The results show that the use of wind speed data from the nearest MERRA or NCEP/CFSR grid points results in an improvement up to 31-33% in correlation coefficient as compared to using data from the nearest NCEP/NCAR grid point. The average improvement in correlation coefficient is about 16% for MERRA and 15% for NCEP/CFSR as compared to the use of NCEP/NCAR reanalysis data. These results strongly suggest that the use of MERRA and NCEP/CFSR reanalysis datasets represents a relevant improvement in accuracy for MCP results. The higher spatial and temporal resolutions of these reanalysis datasets as compared to NCEP/NCAR allow a better representation of the local wind climate as shown by the larger degrees of correlation with local mast measurements.

Mast	R-value using NCAR data	R-value using MERRA data	R-value using CFSR data	Improvement in R-value using MERRA as compared to using NCAR (%)	Improvement in R-value using CFSR as compared to using NCAR (%)
M1	0.731	0.872	0.870	19.3	19.0
M2	0.716	0.874	0.865	22.0	20.8
M3	0.642	0.821	0.806	28.0	25.6
M4	0.715	0.835	0.825	16.8	15.3
M5	0.807	0.885	0.895	9.6	10.9
M6	0.672	0.880	0.855	31.0	27.2
M7	0.799	0.873	0.869	9.3	8.8
M8	0.738	0.841	0.850	14.0	15.3
M9	0.826	0.856	0.865	3.6	4.7
M10	0.701	0.799	0.819	13.9	16.7
M11	0.806	0.858	0.880	6.4	9.2
M12	0.733	0.826	0.804	12.6	9.6
M13	0.762	0.853	0.863	12.0	13.3
M14	0.773	0.860	0.841	11.2	8.8
M15	0.670	0.850	0.822	26.9	22.6
M16	0.799	0.849	0.853	6.2	6.8
M17	0.635	0.843	0.833	32.7	31.2
M18	0.762	0.848	0.848	11.3	11.2
M19	0.675	0.817	0.805	21.0	19.3
M20	0.700	0.815	0.813	16.3	16.1
M21	0.703	0.814	0.797	15.8	13.5
M22	0.759	0.815	0.826	7.4	8.8
M23	0.695	0.814	0.797	17.1	14.7
M24	0.636	0.748	0.629	17.6	-1.0
			Average improvement (%)	15.9	14.5
			Stdev (%)	7.7	7.3

Table 2: Results from the correlation analysis between wind speed measurements at different mast locations and wind speed data from the closest NCEP/NCAR, MERRA and NCEP/CFSR grid points.

The correlation analysis above described is based on the assumption that the local wind climate at a specific mast location is best represented by the wind data from the nearest reanalysis grid point. The validation of this hypothesis has been tested by analyzing the regression fits between the wind speed measurements of a specific mast and the wind speed data from each grid point besides the closest one. The correlation coefficient, R, resultant from each linear regression fit was stored and plotted against the distance between the location of the mast and of the corresponding grid point.

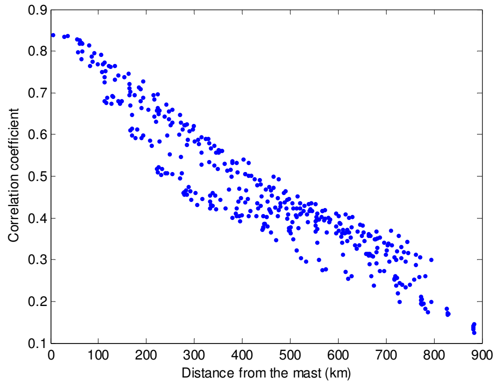


Figure 1: Variation of the degree of correlation with the distance separating the locations of mast M23 and of each NCEP/CFSR grid point.

Figure 1 shows the results obtained for mast M23 when using data from all the NCEP/CFSR grid points. It clearly shows that the degree of correlation between local wind speed measurements and reanalysis wind speed data decreases with increasing distance separating their locations. This result validates the assumption used. However, it is based only on wind measurements from a single mast and on NCEP/CFSR wind data.

Since this validation test requires a very long computing time it was decided to conduct a different analysis involving all the masts but only the NCEP/NCAR (6 out of 19 grid points), MERRA (19 out of 292 grid points) and NCEP/CFSR (20 out of 384) grid points used in obtaining the R-values presented in Table 2. The correlation between the wind speed data from each of these grid points and the wind speed measurements from each mast was analyzed. The degree of correlation should decrease with distance. Table 3 presents the average of the R-values associated with the resultant linear regression.

	NCEP/ NCAR	MERRA	NCEP/ CFSR
Mean R-value	-0.870	-0.886	-0.875
Stdev	0.035	0.039	0.048

Table 3: Correlation analysis between the correlation coefficients between reanalysis data and mast measurements and the distance separating their locations.

Large degrees of correlation were obtained for all the reanalysis datasets with MERRA grid data having a slightly larger mean R-value than NCEP/NCAR and NCEP/CFSR. Furthermore, the mean R-values are negative indicating that the degree of correlation between reference data and local measurements decreases with increasing distance separating their locations. These results validate the hypothesis above described and suggest that the reanalysis datasets are rather consistent in space.

A relevant issue associated with the correlation analysis between mast measurements and reanalysis data is the comparison between point data (site measurements) and grid data. The grid data is representative for the entire grid cell that is, for the latitudes of Sweden, about 138x276 km^2 for NCEP/NCAR, 36x55 km^2 for MERRA and 29x55 km^2 for NCEP/CFSR. The NCEP/NCAR, MERRA and NCEP/CFSR grid data used in this study are attributed to the central points (C) of the corresponding grid cells. The results presented in Table 2 are based on this definition.

How sensitive are the degrees of correlation between wind measurements and reanalysis wind data to different grid point definitions? In order to answer this question, the correlation analysis between mast data and data from the nearest NCEP/NCAR, MERRA and NCEP/CFSR grid points was repeated for the following four grid point definitions: bottom left (BL), bottom right (BR), top left (TL) and top right (TR) corners of the grid cell.

The average differences between the R-values corresponding to each grid point definition and the central point definition (C) are shown in Table 4.

Grid point def.	Average difference of the R-values corresponding to each definition relative to definition “C”		
	NCAR	MERRA	CFSR
C	0	0	0
BL	-0.005	-0.072	-0.003
BR	-0.009	-0.074	-0.004
TL	-0.011	-0.014	-0.012
TR	-0.018	-0.026	-0.014

Table 4: Average of the change in R-value when using different grid point definitions relative to definition C.

The results show that the degree of correlation is in average lower when using the BL, BR, TL and TR definitions than using the central point definition. This suggests that the central point of a grid cell might be the point that best represents the climate conditions of the whole grid cell. However, a similar analysis should be applied to a larger set of masts distributed uniformly over a larger region in order to be more conclusive.

2.2 Long-term trends in reanalysis wind data

A second approach used to investigate the performance of the different reanalysis datasets is the analysis of possible long-term trends present in the reanalysis wind speed data.

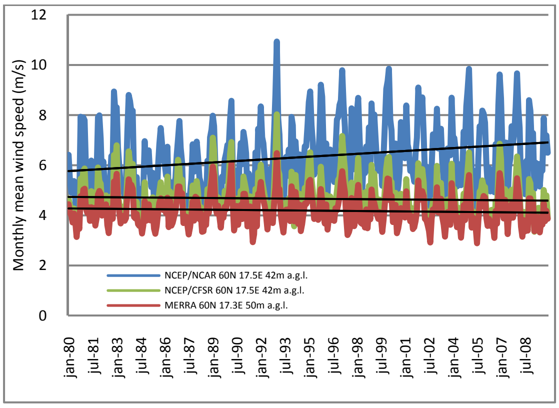


Figure 2: Monthly mean wind speeds from the NCEP/NCAR (blue line), MERRA (red line) and NCEP/CFSR (green line) grid points located nearest to 60°N 17.5°E.

Figure 2 illustrates a case where the NCEP/NCAR wind data from a specific grid point show a strong upward long-term trend while neither MERRA nor NCEP/CFSR data from the nearest grid points show significant long-term trends.

The temporal consistency of the reanalysis data is a key issue for its applicability in MCP analysis. Possible trends present in the data should represent real climate changes. However, modifications in the observational systems and possible shortcomings of the assimilating model may result in artificial trends or shifts in the resulting reanalysis data. The consistency of the NCEP/NCAR wind data has been discussed previously in a paper by Brower [8]. A number of cases were presented where NCEP/NCAR reanalysis wind data from grid points located in the United States showed significant trends not present in measurements from surface stations.

A temporal consistency analysis was conducted for each of the reanalysis datasets included in this study. Wind speed data covering the period 1980-2009 from each of the NCEP/NCAR, MERRA and NCEP/CFSR grid points located in the Swedish territory were analyzed (19 NCEP/NCAR, 292 MERRA and 384 NCEP/CFSR grid points). By finding the linear regression that best fits the wind speed series against the sample number, the slope value, *k*, of the resultant linear fit was obtained for each grid point analyzed. Since the different reanalysis datasets have different sampling periods, the regression fits were applied to wind speed series with a common sampling period of 6 hours extracted from the full resolution time series. This allows the comparison between the k-values obtained for the different reanalysis grid points. Furthermore, the ratio k/k_{min} was computed for each grid point in order to facilitate the comparison. k_{min} is the minimum value of all the k-values and corresponds to the k-value of the NCEP/CFSR 64,5ºN 21ºE grid point, that is equal to 9.35×10^{-9} $ms^{-1}sample^{-1}$.

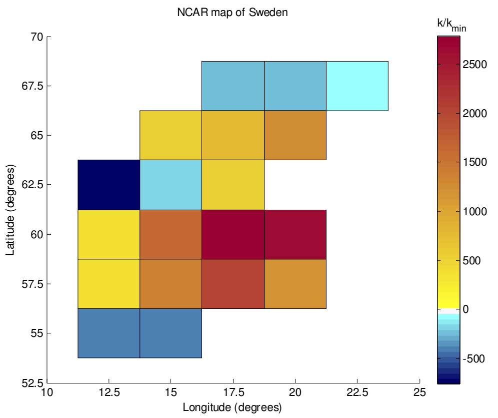
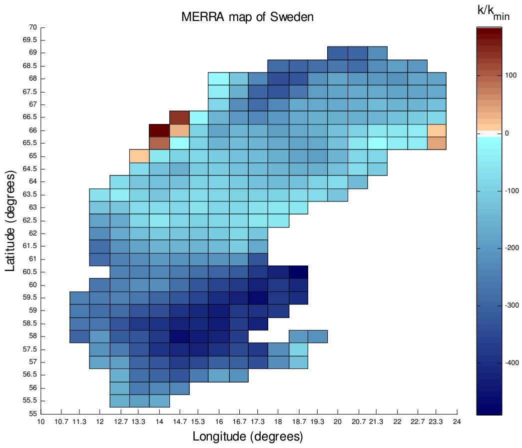


Figure 3: Image plot of the k/k_{min} values for the NCEP/NCAR grid points analyzed.



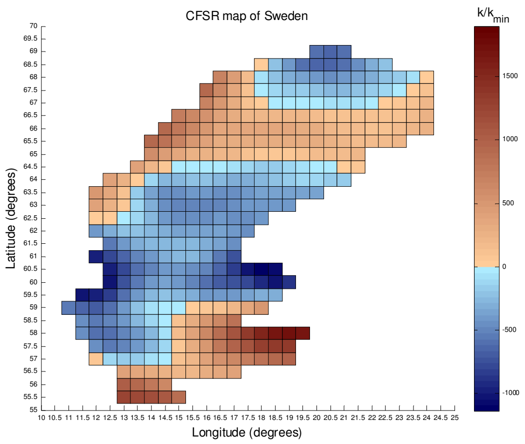


Figure 4: Image plot of the k/k_{min} values for the MERRA grid points analyzed.

Figure 5: Image plot of the k/k_{min} values for the NCEP/CFSR grid points analyzed.

Figures 3, 4 and 5 show the image plots of the k/k_{min} values obtained for NCEP/NCAR, MERRA and NCEP/CFSR grid points, respectively. Note that the color scale differs between the figures. Table 5 summarizes the main results from this analysis.

The results show that NCEP/NCAR and NCEP/CFSR wind data show the strongest long-term trends. Furthermore, the trend appears to be upward for 12 of the 19 NCEP/NCAR grid points analyzed (Figure 3). Wind speed data from the NCEP/CFSR grid points located in southeast Sweden as well as in the region between 65-67º latitude show upward long-term trends while downward trends are observed for the other grid points (Figure 5). MERRA shows mainly downward long-term trends (Figure 4) significantly weaker than observed for NCEP/NCAR and NCEP/CFSR. The observed trends are in average about 80% weaker for MERRA than for NCEP/NCAR while NCEP/CFSR show 60% weaker long-term trends than NCEP/NCAR (Table 5).

Reanalysis data	Range of k/k_{min}	Mean value of $\lvert k/k_{min}\rvert$	Standard deviation of $\lvert k/k_{min}\rvert$
NCEP/NCAR	[-755.6 ; 2784.8]	939.9	806.8
MERRA	[-488.9 ; 184.5]	198.4	111.1
NCEP/CFSR	[-1136.8 ; 1719.5]	394.0	309.7

Table 5: Results from the temporal consistency analysis performed on the different reanalysis datasets.

The long-term variation of the wind potential in Germany was discussed in a paper by Albers [9]. Albers refers to a study by Schmidt [10] who analyzed geostrophic wind data back to 1879 at the German North Sea coast. Schmidt concluded that no real long-term trends regarding the wind potential can be observed since 1879 in that region. Moreover, large variations were observed with a predominant but not consistent cycle of about 35 years.

Wern et al. [11] investigated the variation of the mean wind speed in Sweden during the period of 1951-2008. Pressure measurements have been used to calculate the geostrophic wind speed in 11 different triangles covering Sweden. Wern et al. concluded that the annual mean wind speed for the period of 1951-2008 presents a downward long-term trend in 10 of the 11 triangles analyzed.

The observation of weak downward long-term trends for the majority of the MERRA grid data is in accordance with the results by Wern et al. [11]. The strong upward trends observed in some of the NCEP/NCAR and NCEP/CFSR grid data are most probably a signature of inconsistency resultant from possible modifications in the observational systems and/or shortcomings of the assimilation models.

2.3 Influence of the choice of reanalysis data on the energy production estimate – Case study

In order to investigate how the choice of reanalysis data influences the energy production estimates, a case study was performed based on 3 years of wind measurements (2007-2009) from the met mast M11 and the closest reanalysis grid points. Table 6 summarizes the results obtained.

Grid points	Distance from the mast (km)	R-value on wind speed	Trend (k/k_{min})	Energy correction factor	Relative difference in the energy estimate compared to using NCAR 57.5ºN 15ºE
NCAR 57.5ºN 15ºE	66	0.806	+1393	0.93	-
MERRA 57.5ºN 14.7ºE	61	0.817	-412	1.06	+14%
CFSR 57.5ºN 14.5ºE	60	0.852	-106	1.10	+18%
MERRA 58.0ºN 14.7ºE	10	0.858	-458	1.07	+15%
CFSR 58.0ºN 14.5ºE	0	0.880	-79	1.09	+17%

Table 6: Influence on the energy production estimate of the choice of reanalysis data.

The location of the met mast M11 is 58,04ºN 14.51ºE almost collocated with the NCEP/CFSR 58ºN 14.5ºE grid point and closely located to the MERRA 58ºN 14.7ºE grid point. The larger R-values obtained for these two grid points are most probably explained by their proximity to the met mast. The energy correction factors presented in Table 6 result from the application of the wind index correlation MCP method. Thøgersen et al. [12] gives a detailed description of this method.

The k/k_{min} values for each grid data analyzed are also presented in Table 6. The 57.5ºN 15ºE NCEP/NCAR grid point presents a quite strong upward trend. All the other grid points show rather weak downward long-term trends. Furthermore, NCEP/NCAR 57.5ºN 15ºE is the grid point located farthest from the met mast location. The performance of MCP based on wind data from this grid point is therefore highly uncertain for this specific case.

The energy correction factors obtained using MERRA and NCEP/CFSR grid data are significantly different as compared to the results obtained using NCEP/NCAR 57.5ºN 15ºE grid data. The results differ up to 18%. This is a highly significant difference when estimating the energy production of a wind farm.

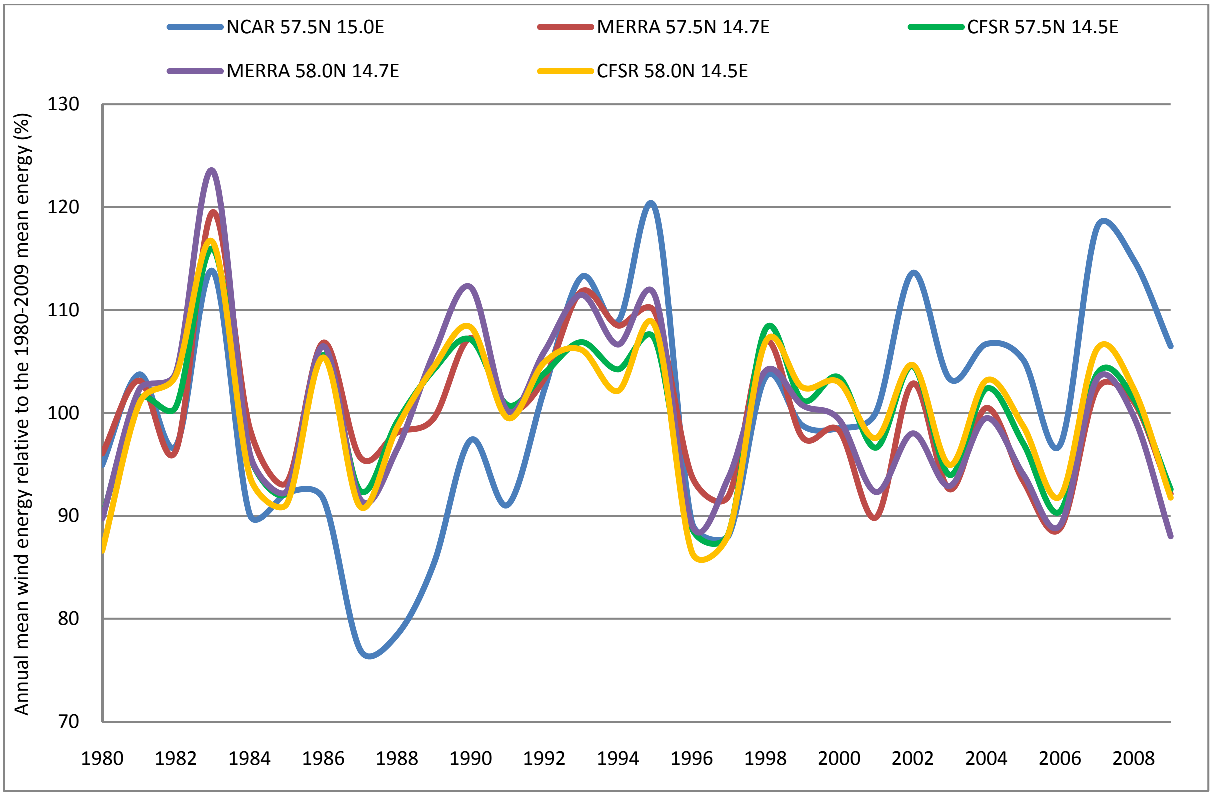


Figure 6: Annual mean wind energy relative to the mean energy of the period 1980-2009.

Figure 6 shows the annual mean wind energy relative to the mean energy for the period of 1980-2009 for each of the grid data analyzed in this case study.

One may see that NCEP/NCAR 57.5ºN 15ºE wind data show significantly larger mean wind energy for the measurement period (2007-2009) than for the period of 1980-2009. Consequently, the MCP procedure results on a factor less than 1 in order to correct for this effect. On the other way, the energy correction factors are greater than 1 for all the other grid points, resulting in an upward correction of the measured wind energy.

The following conclusions may be drawn from this case study.

- The distance to the local measurements is an important factor when deciding which reanalysis grid point should be used in the long-term correction of measurements. The use of grid data from the closest location to the measurement site results in the highest degree of correlation, in accordance with the results from Section 2.1.
- The comparison between the values presented in rows 1 and 2 shows that the use of grid data with different long-term trends might influence the energy estimate by 14%. Note that these grid points are closely located to each other. This is a highly significant difference when estimating the energy production of a wind farm.
- The total relative difference in energy estimate when using different MERRA and NCEP/CFSR reanalysis data as compared to using NCEP/NCAR data has for this specific case a maximum

value of 18% and a mean value of 16%.
- The use of the four MERRA and NCEP/CFSR grid points give a mean energy correction factor of 1.08, associated with an uncertainty of 1.5% in energy (standard deviation).

It should be noted that the only MCP method applied in this case study was the wind index correlation method using a 30-years reference period. The performance analysis of different MCP methodologies and of different reference periods is outside the scope of this paper.

3 Conclusions

The following conclusions may be drawn from the results presented in this report.

- The fine spatial and temporal resolutions of the MERRA and NCEP/CFSR reanalysis wind data contribute with considerable improvements in the degree of correlation with local wind speed measurements. An average improvement of 16% was obtained using MERRA grid data and 15% using NCEP/CFSR as compared to using NCEP/NCAR. The maximum observed improvement was 33% using MERRA and 31% using NCEP/CFSR.
- All the three reanalysis datasets appear to be rather consistent in space. The degree of correlation between mast measurements and grid data decreases with increasing distance separating the measurement site and the grid point location.
- However, NCEP/NCAR data show for some grid points large temporal inconsistencies that affect considerably the energy production estimates. The relative difference in energy estimate is for a specific analyzed case about 14% when comparing the results obtained using rather inconsistent NCEP/NCAR grid data and fairly consistent MERRA grid data.
- MERRA grid data show significantly weaker (80%) long-term trends than NCEP/NCAR. The trends observed for NCEP/CFSR are in average stronger than observed for MERRA but weaker (60%) than for NCEP/NCAR.
- A predominant upward trend is observed for NCEP/NCAR as well as for part of the NCEP/CFSR grid data. However, MERRA data show predominantly weak downward long-term trends. This result is in accordance with the downward long-term trend observed in the mean wind speed in Sweden during the period of 1951-2008 as reported by Wern et al. [11].
- Observed long-term trends should be investigated for each specific case through comparison with long-term measurement series and/or production data from operational wind farms, if available.
- The uncertainty associated with the MCP procedure should reflect the temporal consistency of the used reanalysis data, as well as the performance of the reanalysis data on characterizing the wind climate at the measurement site.

4 Future Work

This study focuses on the analysis of NCEP/NCAR, MERRA and NCEP/CFSR wind speed data. A similar analysis performed on reanalysis wind direction data would be of great interest.

The causes of the large temporal inconsistency observed in some of the NCEP/NCAR and NCEP/CFSR grid data should be analyzed in more detail. Furthermore, how to correctly judge the uncertainty inferred by long-term trends in the energy estimate should be further investigated.

Although ERA-Interim is not free for commercial uses, the investigation on the use of ERA-Interim reanalysis data and comparison with other reanalysis data would be very interesting.

Acknowledgements

The NCEP/NCAR reanalysis data used in this investigation was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA. The NCEP/CFSR data are from the NOAA's National Operational Model Archive and Distribution System (NOMADS) which is maintained at NOAA's National Climatic Data Center (NDCD). The authors would also like to acknowledge the Global Modeling and Assimilation Office (GMAO) and the GES DISC (Goddard Earth Sciences Data and Information Services Center) for the dissemination of MERRA.

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