Improving uncertainty estimates: Inter-annual variability in Ireland

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Abstract. This paper addresses the uncertainty associated with inter-annual variability used within wind resource assessments for Ireland in order to more accurately represent the uncertainties within wind resource and energy yield assessments. The study was undertaken using a total of 16 ground stations (Met Eireann) and corresponding reanalysis datasets to provide an update to previous work on this topic undertaken nearly 20 years ago. The results of the work demonstrate that the previously reported 5.4% of wind speed inter-annual variability is considered to be appropriate, guidance is given on how to provide a robust assessment of IAV using available sources of data including ground stations, MERRA-2 and ERA-Interim.

1. Introduction

1.1 Wind resource assessment
In order to calculate the financial value of a proposed wind energy development, before construction takes place, a robust understanding of the site’s wind resource is required. The revenue of a project is derived from the energy that the project can produce and the price at which that energy can be sold.

The energy produced by wind turbines comes from the wind, hence the requirement for a wind resource assessment. This field which relies on principles of meteorology, physics, statistics and engineering is one that is developing rapidly and has been over the last 30 years. The typical wind resource assessment includes the following steps:

- On-site measured data analysis;
- Long-term wind resource assessment;
- Wind flow modelling;
- Loss assessment;
- Uncertainty assessment.

On-site measurements of the wind parameters of the site, are typically only available for a period of one to two years, this is a limited period of time when compared to the likely 20-year operational lifetime of a wind energy project. Wind speed varies from year to year and therefore a long-term adjustment of the on-site measured data is desirable.
In addition to the long-term adjustment the inter-annual variability needs to be understood in order for the uncertainty related to these predictions to be quantified. Greater understanding of the long-term wind resource and the inter-annual variability will lead to more robust predictions of the financial value of a wind energy project.

1.2 Inter-annual variability
Inter-annual variability (IAV) is a measure of the extent to which wind speeds vary from one year to the next. IAV is defined as the standard deviation of annual mean wind speed over several years. This value is typically represented as a percentage. Inter-annual variability typically impacts on “anywhere between 10 % and 25 % (figures representing both historic and future wind variability) of the overall uncertainty” [1] over a 10-year return period.

Whilst the calculation of IAV is simple, deriving a site-specific or even regional representative value is not so straightforward. Wind measurements for development projects are typically carried out on-site over a short-term period using a meteorological mast, and more recently remote sensing devices such as SoDAR (Sonic Detection and Ranging) and LiDAR (Light Detection and Ranging) devices. These campaigns last a minimum of 12 months, and after this point it is usually in the interest of the project developer to achieve construction as soon as possible. For this reason the majority of site measurement campaigns are of short duration and therefore a site specific figure of IAV using on-site measurements alone is not possible. If there are no on-site long-term sources, then an alternative source of long-term reference data is required.

1.3 Long-term reference sources
There are two primary types of wind data source used for long-term correction of measured data. Firstly: actual measurements, usually taken by a national meteorological organisation using anemometers. Secondly: virtual datasets, consisting of data from models (both reanalysis and mesoscale models).

With any source of long-term reference there are two key criteria for their use within a long-term assessment. Firstly they need to be consistent – providing a true representation of the long-term variation historically. Secondly they need to be representative of the site being modelled – often measured through criteria such as correlation.

1.3.1 Actual measurements
In Ireland the primary source of long-term reference data comes from Met Eireann, Ireland’s National Meteorological Services. Met Eireann has a network of 25 surface meteorological stations spread across the country; these typically consist of a meteorological mast with an anemometer mounted on it at a height of 10 m above ground level.

Each meteorological station has metadata available (logs detailing sensor changes, mast movements and exposure changes). Using the metadata it is possible to make a judgement to ensure that the readings from the station can be considered consistent.

1.3.2 Virtual datasets
Reanalysis datasets take historical meteorological measurements from a variety of sources, including surface-based stations, rawinsonde, satellites, aircraft measurements, etc. and apply a model which is used to predict the states of the weather at different times and locations. One output of some of these models is the surface wind speed – which is of use for wind energy professionals as a source of long-term reference.

Within this study two commonly used reanalysis models are considered: 1) The MERRA-2 (Modern Era Reanalysis for Research and Applications-2) [2] datasets with a horizontal resolution of 0.5° x 2/3°
and a temporal resolution of an hour; 2) The EMD-ERA (based on ERA-Interim) datasets [3] with a horizontal resolution of approximately 80 km and a temporal resolution of 6 hours.

One of primary limitations of reanalysis data sources in relation to assessing long-term wind speeds for a site is whether the model can be considered to be consistent. Several papers have been published attempting to validate the consistency of reanalysis data sources over time [4], [5], [6], [7]. The use of reanalysis data sources has been previously studied in South Africa [1] and this study applies a similar approach to Ireland.

1.4 Previous Studies
The literature available on the inter-annual variability of wind speeds internationally is fairly limited. From experience the current industry standard is to use a figure of ~6 % (annual mean wind speed) that is applicable to North Western Europe and based on a study from 1997 [8]. This study presents an IAV figure for Ireland of 5.4 % [8], based on five meteorological stations covering a cumulative time period of 144 years.

Studies of the IAV in the United States [9] and South Africa [1] have recently been published. Both of these studies examine whether reanalysis sources may be appropriate for representing the IAV in these two regions. The South Africa study concluded that whilst reanalysis models may be of use in informing the site IAV, adjustments are required as there may, in some cases, be under prediction of the IAV.

1.5 Summary of Objectives
The study aims are to address the following areas:

- Determine a general IAV figure (or range) applicable to Ireland – in order to compare this to the current industry standard of 5.4%. The results may challenge historic industry assumptions.
- Determine if a consistent relationship exists between the IAV derived from ground stations and the reanalysis models, informing of the ability of global reanalysis models to guide the site IAV assumptions.
- Determine the length of data period required for the IAV to converge on a consistent value.

The aim of the study is to provide practical guidance on the best approach to evaluate IAV in Ireland for wind energy projects. The results will be useful for stakeholders within the wind energy industry including wind resource analysts, developers, owners, operators, meteorologist, research institutes and financial investors.

2. Methodology

2.1 Input Data
Long-term wind data from all 25 Met Eireann stations has been obtained. For each of the Met stations, the nearest MERRA-2 [2] and ERA-Interim [3] nodes have also been downloaded. For these nodes a height above ground level of 50 m was used throughout the analysis.

2.2 Data Screening
Following the accumulation of input data a screening process was undertaken in order to remove datasets which contained inconsistencies or were not of sufficiently long a period to be of use.
Station inconsistencies were detected through the use of a changepoint analysis method [10] and metadata review. The metadata review consisted of examination of the records for each station in order to identify the following:

- Changes in the measurement equipment, such as anemometer make or model, mast location or data recording system.
- Changes in the exposure surrounding the site, such as growing trees, new buildings or obstacles located near to the measurement station.

The changepoint analysis method is documented within [11] and the application of the approach also recorded through [10]. The changepoint analysis represents a statistical technique, based on bootstrapping, which calculates a probability of inconsistency within a time series of data, this technique when applied to monthly-mean wind data has been demonstrated to have a high accuracy, and particularly useful for wind analysis a low false negative rate [10].

Following the screening process 16 datasets remained for use within the study. These are displayed in Figure 1.

![Figure 1. Locations of reference stations studied](https://example.com/figure1.png)

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### 2.3 IAV Calculation

Following the completion of the site identification and screening processes the IAV was calculated for each site from the ground stations and nearby MERRA-2 and ERA-Interim nodes. The IAV was calculated both for the concurrent period with the ground station and also for the full period. This allows for an understanding of whether the period of ground measurements could be considered as representative of the long-term.
2.4 Relationship between datasets
The second objective of the work was to determine whether any relationship between the datasets existed, in terms of their IAV. A comparison between the short-term and long-term IAV figures was calculated for each site, this was performed as a simple ratio of short-term to long-term.

2.5 Period required for convergent IAV
In order to determine the period of data required for the IAV figure to converge, a cumulative (going backwards in time) standard deviation was calculated. This started with the most recent three whole years (2014 to 2016) and was extended by including additional years until the length of the reference dataset was reached.

The IAV development over period was plotted and convergence was considered to be achieved at the period in which the IAV value is within +/- 15 % of the full period IAV, this approach is consistent with that from a previous study of South Africa [1]. Within this approach there is a trade-off between reaching a fully converged figure and the number of data sources with the required length of data available. Studies have shown the large drop off in the number of available consistent reference station sources as time period increases [7]. For obvious reasons, such as improving technology and greater understanding of the importance of consistency, wind speed measurements going back further than 20-years are often not of a similar quality to those from modern sensors. For reanalysis sources this is not typically a problem (as the data sources consist of data covering a long historic period of usually greater than 30 years), however for comparison with ground stations a higher convergence figure is required.

3. Results

3.1 IAV calculation
The results are presented in Table 1. following the aforementioned screening of the datasets, these results were based on a total of 174 years of measured wind data. It should be noted that these results are a percentage of wind speed.

|                    | Ground Station | MERRA-2 | ERA-Interim |
|--------------------|----------------|---------|-------------|
| Minimum            | 4.4 %          | 3.0 %   | 3.0 %       |
| Mean               | 5.4 %          | 4.1 %   | 4.0 %       |
| Maximum            | 6.9 %          | 5.7 %   | 4.7 %       |

3.2 Relationship between datasets
The results demonstrate that across all sites MERRA-2 and ERA-Interim under-predict the IAV at the corresponding ground station. The results vary from approximately 50 % to 100 % of the ground station IAV with both of reanalysis sources producing very similar mean figures – these can be seen in Table 2.

|                   | MERRA-2: Ground Station | ERA-Interim: Ground Station |
|-------------------|-------------------------|-----------------------------|
| Minimum           | 58.2 %                  | 56.7 %                      |
| Mean              | 76.8 %                  | 74.3 %                      |
| Maximum           | 100.0 %                 | 89.6 %                      |
3.3 Period required for convergent IAV
Following the methodology outlined previously, the change in IAV over time was calculated for each site and reanalysis source. An example is given in Figure 2, the overall results for all 16 sites are given in Table 3. This plot shows how the IAV converges on the long-term figure and +/- 15% bounds are applied, the 15% convergence is selected based on previous studies [1]. It can be seen that for this site convergence is achieved after 11 years.

![Figure 2. Plot of change in IAV (for a single reference site) with increasing data period (black line), +/- 15 % limit for convergence plotted (red dashed line)](image)

| Table 3. Data period (years) required for converged IAV |
|--------------------------------------------------------|
| Ground station | MERRA-2 | ERA-Interim |
| Minimum        | 4.0     | 6.0         | 7.0         |
| Mean           | 8.8     | 8.5         | 10.4        |
| Maximum        | 13.0    | 11.0        | 23.0        |

4. Conclusions

4.1 IAV in Ireland
The mean IAV across the Met Eireann ground stations was calculated to be 5.4%. This agrees with the previously calculated figure from a study in 1998 [8]. The previous study, whilst considering longer time periods from each of the five stations used, was limited in the spatial coverage. The combination of these two studies – greatly increases confidence in the IAV figure. The agreement between the two studies is re-assuring, whilst some of the ground stations considered within are the same (although covering different time periods) some stations are different between the studies. Combined the two studies include a total of 318 years of reference data from 16 independent sources. This is considered a comprehensive sample to represent the IAV.

It is noted that the IAV figure does vary between sites with a range from 4.4% to 6.9% (for reference the previous study [8] ranged from 4.7% to 6.4% across the five ground stations). From analysis it is not clear as to the cause of this variation, no clear trends are observed in terms of coastal against non-coastal or geographically. Local measurements are recommended wherever possible, however it is considered that the mean figure for Ireland of 5.4% is a robust assessment and can be used within energy yield assessments.
4.2 Reanalysis data as a source of IAV
The study has examined how well the reanalysis data sources MERRA-2 and ERA-Interim represent the IAV measured at ground stations. A strong correlation is not measured ($R^2 < 0.5$) between either source and the surface stations. However from the results it is concluded that both reanalysis models under-predict the IAV, typically by 25%. Care should therefore be taken when considering reanalysis sources within any assessment of site specific IAV.

The lack of relationship between reanalysis data and ground measurements agrees with a study in South Africa [1]. It is speculated that the reanalysis inter-annual variability is lower than this derived from measurements due to the setup of the model, that typically reanalysis does not pick up on inter-decadal variation particularly well and therefore this results in a lower result.

4.3 Period required for convergent IAV
From this study it is recommended that a data period of a minimum of 10 years is used in order to derive the IAV when using any source of data. This agrees, and is slightly less conservative than, a similar study performed for South Africa [1]. It is considered that the +/-15% figure representing convergence is appropriate due to the impact this level of error is likely to have on the overall wind resource assessment uncertainty. The impact is not negligible; however the authors consider this a reasonable compromise between accuracy and number of available data sources.

4.4 Practical guidance for wind resource assessment
The purpose of this study has been to inform more robust wind resource and energy yield assessments, therefore a few recommendations are given below which should be considered within these analyses.

- Screening of reference sources for consistency is important to ensure representative results.
- When investigating IAV a period of >10 years should be considered to provide a representative sample.
- A figure of 5.4% IAV in Ireland is considered appropriate, however this figure may be refined if local long-term site data is available.
- MERRA-2 and ERA-Interim under-predict IAV, however the level of under-prediction varies and this should be considered if using these data sources to predict IAV.
- A comprehensive justification of the IAV figure should be provided within any wind resource or energy yield assessment in order to allow for thorough review and due diligence.

4.5 Further work
It is becoming clear from the four main studies into the area of inter-annual variability, covered in this study, the USA [9], South Africa [1] and Offshore UK [12], that reanalysis models behave differently across the globe. Therefore a simple global study is considered unlikely to be of sufficient depth to capture local effects. Therefore it is recommended that for new regions this study is repeated in order to ensure that IAV assumptions are accurate within uncertainty assessments.

Addition of further sources of wind data, including operational wind farm data would add benefit to this study. This could confirm the representativeness of the surface stations as a measure of wind farm production variability due to wind speed for a specific wind farm development.

5. References

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