TECHNICAL REPORT

# WRF Time Series (WRFTS) Validation

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# Introduction

For more than four decades, UL Solutions has been developing and running mesoscale numerical weather prediction (NWP) models (e.g., Kaplan et al., 1982). For the past ten years, the Weather Research and Forecasting (WRF) model developed by the Nation Center for Atmospheric Research (NCAR) and others has been the model of choice at UL Solutions and in the wind energy industry for generating meteorological time series. Time series spanning 20 to 30 years is necessary for wind resource assessment and is primarily used to adjust short-term onsite measurements to the long-term wind climate and to estimate the wind speed fluctuations from year to year, i.e., inter-annual variability (IAV), provide necessary meteorological inputs to icing modeling, time series energy modeling, etc. UL Solutions offers an hourly[1] WRF time series for these wind energy applications.

This study aims to validate the WRF time series by UL Solutions in both onshore and offshore environments. To help put things in perspective, the leading reanalysis dataset ERA5 from the European Centre for Medium-Range Weather Forecasts (ECMWF) is also included.

# ERA5 reanalysis time-series

Reanalysis datasets integrate model data with diverse observation data to create a coherent timeline of climate variables. These datasets span several decades, enabling the exploration of global climate changes and shifts in weather patterns. Prominent reanalysis data sets accessible for public use include MERRA2 and ERA5, respectively, the Modern-Era Retrospective Analysis for Research and Applications, Version 2 from NASA (Molod et al., 2015) and the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (Hersbach et al., 2019).

ERA5 provides hourly data for many atmospheric, land-surface and sea-state parameters. It is produced at an approximately 0.25-degree resolution using ECMWF's Integrated Forecast System (IFS). The atmospheric model within the IFS is coupled with a soil model and an ocean wave model. The atmospheric model contains 137 hybrid sigma-pressure model levels in the vertical direction. Surface or single-level data containing 2-D parameters such as 2-meter (m) temperature and 10 m and 100 m wind components are also available.

UL Solutions provides access to the ERA5 reanalysis data through its Windnavigator platform and Windographer software[2], which are available for any location worldwide. This study extracted the ERA5 time series (ERA5) to validate specific met mast locations. ERA5 was selected for this study due to its established reputation for consistently outperforming other reanalysis models regarding the correlation with observational data (Olauson, 2018; Ramon et al., 2019; Jourdier, 2020; Beaucage & Bhosale, 2021).

# WRF time series

The Weather Research and Forecasting (WRF) model is a state-of-the-art mesoscale numerical weather prediction model (Skamarock, 2004). WRF solves the fully compressible, non-hydrostatic Navier-Stokes equations for the 3-dimensional atmosphere on a gridded domain and uses a complete suite of physical parameterization schemes for sub-grid scale processes.

UL Solutions offers a 20-year WRF time series on the Windnavigator platform . Table 1 provides a quick overview of the WRF configuration at UL Solutions. WRF is initialized by the ERA5 reanalysis data, and the boundary conditions are provided by ERA5 every three hours. The ERA5 reanalysis data with a horizontal resolution of 0.25 degrees is dynamically downscaled with WRF simulations to a 3-kilometer grid spacing for an hourly time series.[3] This dynamical downscaling allows the proper cascade of energy between the WRF nested grids. The final grid spacing of 3 km helps ensure that WRF can realistically reproduce the hourly, 10-minute wind speed ramps. In addition, a final grid spacing of 3 km enables WRF to capture important wind patterns (e.g., channeling through mountain passes, katabatic winds, mountain waves, lake and sea breezes, low-level jets) and temperature gradients (temperature inversions, thermal stability, etc.), as well as explicitly resolving clouds, which strongly influence icing conditions for rime ice and freezing rain.

| Features | WRF options |
|---|---|
| Initial and boundary conditions | ERA5 reanalysis |
| Topographic data | Shuttle radar topography mission (SRTM)<br>(3 arc-second resolution) |
| Land cover data | In-house, global dataset.[4,5]<br>(3 arc-second resolution) |
| Data assimilation | Spectral nudging |
| Sea surface temperature data | From reanalysis data |
| Physics parameterization | N/A[6] |

*Table 1: WRF Configuration by UL Solutions*

# MET observation data

Seventy-one quality-controlled meteorological masts and lidars covering each region of the world were selected for use in the validation of the WRF and ERA5 time series. These masts had data recovery above 80%, at least one year of valid data, and measurement heights ranging from 50 m to 140 m above ground level (AGL). They were also selected for their geographic representation. Table 2 and Figure 1 show the distribution of meteorological masts (met masts) across different regions. We selected stations to ensure our observations cover all parts of the globe, representing different wind patterns and their variability.

| Region | Number of onshore/offshore stations |
|---|---|
| Africa | 6 |
| Asia | 13 |
| Europe | 9 (12) |
| North America | 13 (7) |
| Oceania | 2 |
| South America | 9 |

*Table 2: Validation sites by region*

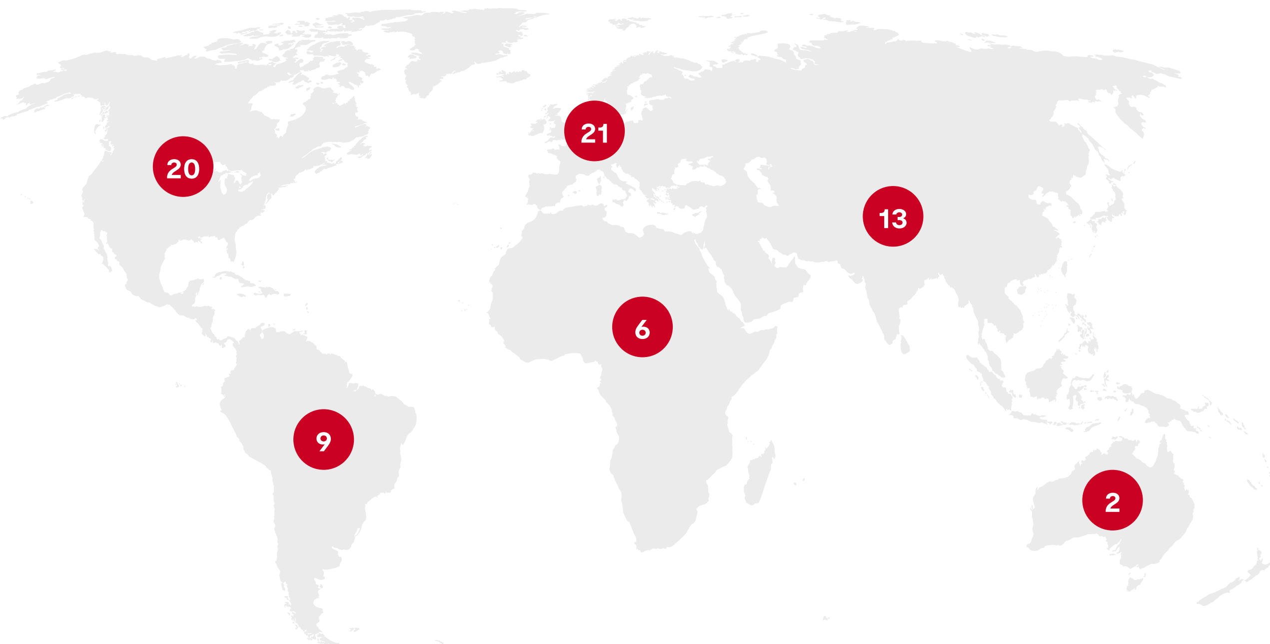


*Figure 1: Region wise spread of mast locations used for the validation*

# Validation of WRF time series

To evaluate the accuracy of the WRF-derived wind speeds, we validated the modeled data against onsite measurements. Since the ERA5 data is available at 100-m AGL, we extracted the WRF time series at the same height. For consistency, we extrapolated the observation data to 100 m using the wind profile power law. We restricted the data to concurrent periods to ensure a fair comparison. The skills of the WRF model and the ERA5 reanalysis were evaluated based on standard error metrics, including the mean bias, root mean square error (RMSE) and coefficient of determination ($R^2$).

# Onshore sites

Fifty-two met mast, or remote sensing observations, were used for the validation exercise at onshore sites. Table 3 displays the hourly and daily statistics for mean bias, mean absolute error (MAE), root mean square error (RMSE), the coefficient of determination, and $R^2$ values for wind speed. The plus or minus signs indicate the standard deviation from the mean.

Table 3 demonstrates that WRF outperforms ERA5 in all error statistics, even though the mean $R^2$ values are close. The wind speed mean bias of ERA5 is considerable compared to WRF, -2.28 m/s vs. -0.52 m/s respectively. Clearly, the finer grid spacing of the WRF model helps capture the topographic forces and, thus, modeling the local wind flow. In addition, ERA5 has a negative bias at all onshore locations, indicating that ERA5 consistently underpredicts the mean wind speeds. This is not surprising because of the coarse spatial resolution of ERA5, which tends to smooth the wind field and the fact that the observations are generally installed in areas windier than their surroundings (e.g., hilltops) to develop wind farms. Conversely, the WRF time series exhibits lower MAE and RMSE, indicating better accuracy overall than ERA5. In general, the hourly RMSE of NWP models is roughly above 3 m/s for sites located in moderate or complex terrains (e.g., Solbakken et al., 2021; Fernandez-Gonzalez et al., 2018; Banks et al., 2016; Brower, 2009; Seaman, 2000).

Figure 2 illustrates the distribution of $R^2$ values at all onshore locations, highlighting the consistency of the WRF dataset compared to the ERA5 dataset. The mean $R^2$ correlations for both datasets are similar, but the WRF dataset exhibits less variability in $R^2$ values across the different locations. This absence of discontinuity in the WRF time series dataset suggests it's more reliable and consistent than the ERA5 dataset. The box and whisker plot in Figure 3 indicate this more significant variability in the ERA5 $R^2$ distribution. Overall, these figures demonstrate the advantages of using the WRF time series dataset over the ERA5 dataset for wind energy assessment studies. To our knowledge, only two studies have compared WRF model outputs to ERA5: Pronk et al. (2021) which shows ERA5 outperforming WRF, while Svenningson et al. (2020) shows WRF outperforming ERA5 by approximately 0.03 on the hourly $R^2$. Note that the hourly $R^2$ correlation for the observations and modeled wind time series is highly site-dependent and can vary widely (see Fig. 2).

Figure 4 shows the diurnal wind speed profile at a specific station in North America. Notably, the figure reveals a known[7] discontinuity in the ERA5 time series between 9:00-10:00 and 21:00-22:00 UTC. This discontinuity is due to the 12-hour data assimilation cycle in ERA5. Even though WRF gets its initial and boundary conditions from ERA5, the WRF simulation is not impacted by the ERA5 discontinuity.

| | WRF | ERA5 | WRF | ERA5 |
|---|---|---|---|---|
| Error statistics | Hourly | | Daily | |
| Mean bias | -0.52 (±0.89) | -2.27 (±1.17) | -0.52 (±0.89) | -2.28 (±1.17) |
| MAE | 1.98 (±0.47) | 2.68 (±0.98) | 1.29 (±0.48) | 2.36 (±1.12) |
| RMSE | 2.58 (±0.61) | 3.31 (±1.13) | 1.61 (±0.55) | 2.64 (±1.17) |
| R-squared | 0.60 (±0.11) | 0.58 (±0.15) | 0.80 (±0.11) | 0.79 (±0.15) |

*Table 3: Error statistics of wind speeds at 52 onshore sites*

# Offshore sites

For the validation of WRF and ERA5 time series at offshore sites, 19 offshore met mast or floating lidar observations were used. As shown in Table 4, the WRF model exhibits a mean bias closer to 0 m/s than the ERA5 reanalysis. The WRF mean bias of -0.23 m/s or -2.8% is similar to the mean bias shown in other offshore studies at some of the same offshore met masts (Pronk et al., 2021; Hahmann et al., 2020; Olsen et al., 2017; Hahmann et al., 2015). The same applies to the hourly RMSE. NWP models generally yield hourly RMSE in the 2 m/s to 3 m/s range for sites in relatively flat terrains or offshore (e.g., Hahmann et al., 2020; Floors et al., 2018; Olsen et al., 2017; Hahmann et al., 2015). Although WRF outperforms ERA5 on the mean bias, ERA5 performs slightly better than WRF when considering other error metrics, such as the RMSE and the hourly $R^2$ correlation, as shown in Table 4. As surprising as this result may seem, the study by Pronk et al., 2021 came to a similar conclusion. The seminal paper by Mass et al., 2002 probably offers the best explanation: "Decreasing grid spacing in mesoscale models to less than 10-15 km generally improves the realism of the results but does not necessarily significantly improve the objectively scored accuracy of the forecasts."

| | WRF | ERA5 | WRF | ERA5 |
|---|---|---|---|---|
| Error statistics | Hourly | | Daily | |
| Bias | -0.23 (±0.35) | -0.56 (±0.27) | -0.23 (±0.34) | -0.55 (±0.26) |
| MAE | 1.43 (±0.21) | 1.39 (±0.23) | 0.76 (±0.22) | 0.82 (±0.22) |
| RMSE | 1.89 (±0.29) | 1.83 (±0.28) | 0.99 (±0.31) | 1.04 (±0.27) |
| R-Squared | 0.84 (±0.03) | 0.86 (±0.04) | 0.95 (±0.02) | 0.95 (±0.03) |

*Table 4: Error statistics of wind speeds at 19 offshore sites*

# Conclusions

UL Solutions performed a validation of its WRF time series at 52 onshore sites with varying terrain complexity, land cover and wind climates around the world. In addition, 19 offshore sites in the USA and Europe were included in the validation. The evaluation of the WRF and ERA5-derived wind speeds reveals some notable differences. For onshore sites, the WRF time series performs significantly better than ERA5 across all error statistics, including mean bias, RMSE, and $R^2$, although by a small margin on the coefficient of determination. As some may have expected, WRF is not a clear winner over ERA5 for offshore sites. In offshore environments, WRF performs better than ERA5 on the mean bias, but ERA5 performs slightly better than WRF on the MAE, RMSE and the hourly $R^2$ correlation. A study by Pronk et al., 2021 also came to a similar conclusion.

Another advantage of WRF over ERA5 is that discontinuities are often present in the ERA5 reanalysis data around 9:00/10:00 UTC and 21:00/22:00 UTC due to ERA5's 12-hour data assimilation cycle. Our WRF simulations do not exhibit any such spurious jumps. Also, ERA5 provides single-level data only at 10 m and 100 m, whereas WRF time series can be retrieved at any desired height, enabling more accurate analyses.

In the end, we recommend using the WRF time series over ERA5. It is consistent and more accurate; it better captures diurnal and seasonal variations and is suitable for long-term adjustment.

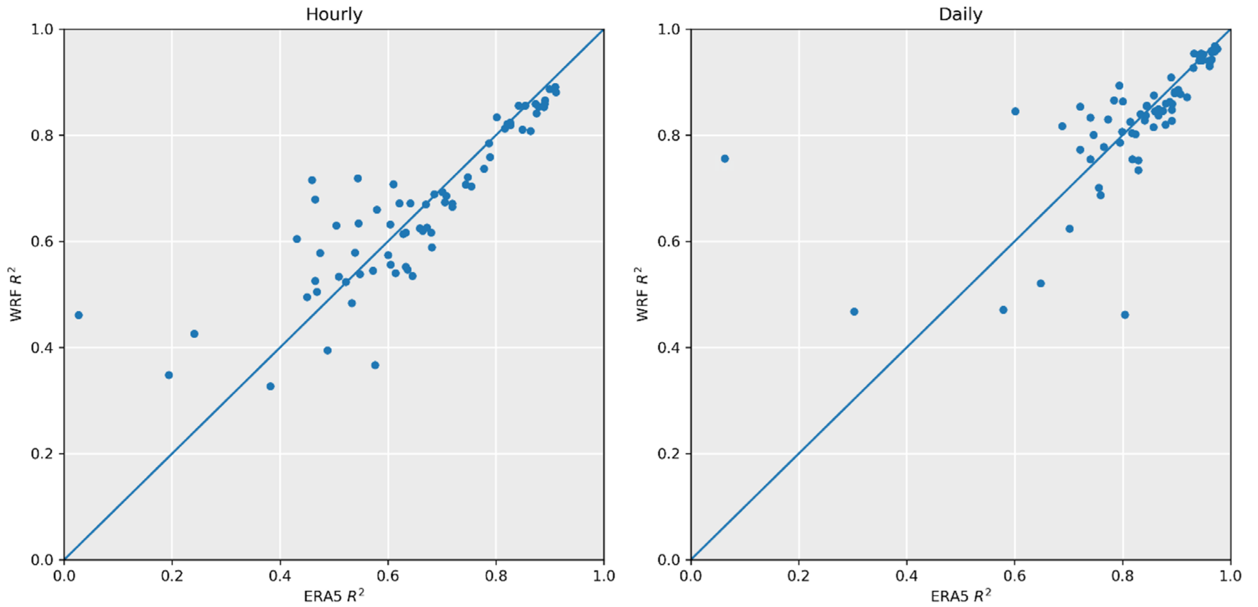


*Figure 2: Scatter plot between ERA5 vs 3km WRFTS*

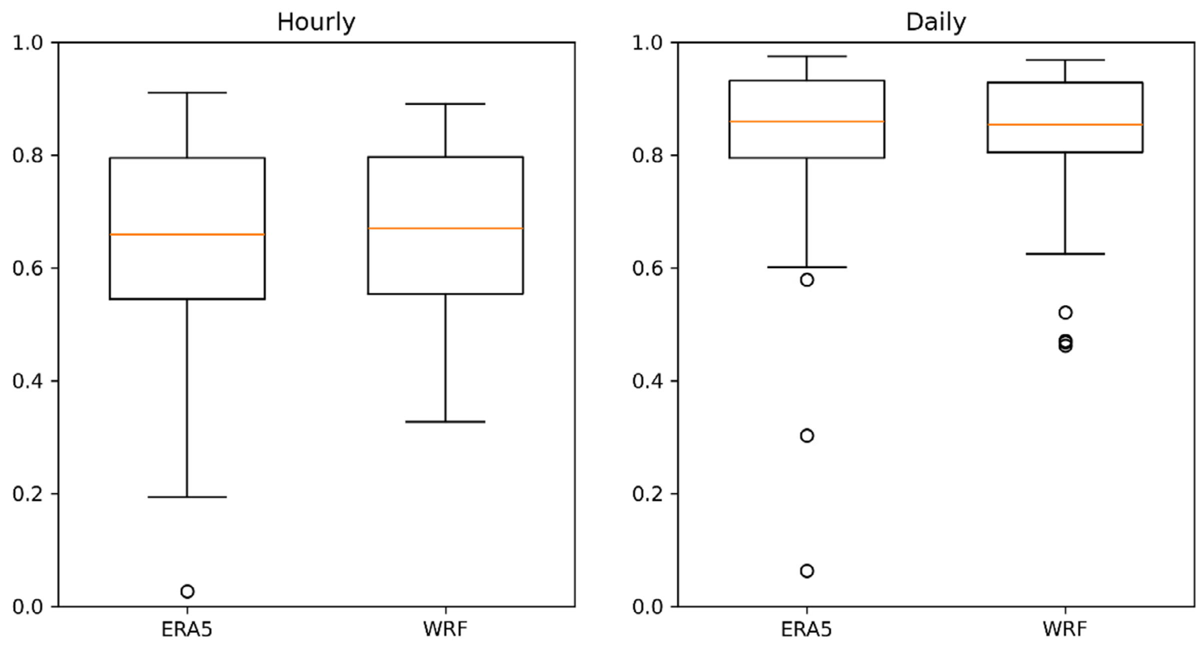


*Figure 3: $R^2$ distribution of hourly and daily mean*

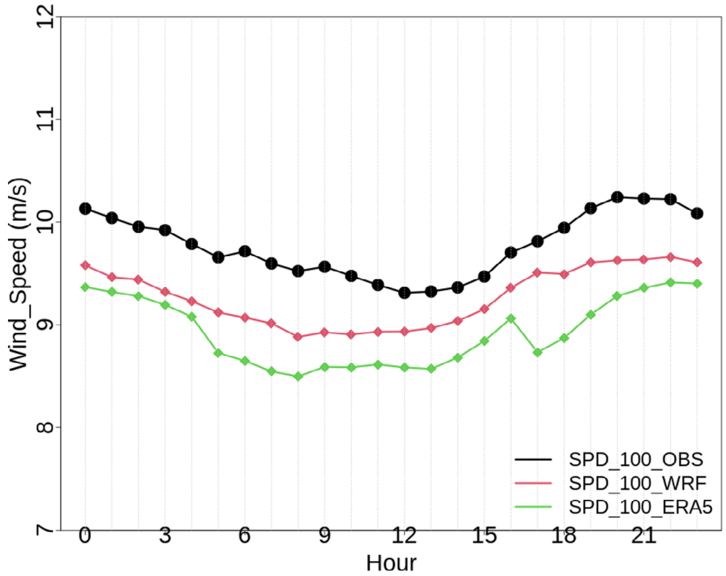


*Figure 4: Mean diurnal windspeed profile at a station in North America*

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# End notes

1. https://wn.ul-renewables.com/
2. https://www.ul.com/software/windographer-wind-data-analytics-and-visualization-solution
3. UL Solutions can also provide 10-minute WRF time series upon request.
4. WRF time series going back to 1979 are available upon request.
5. A mix of NLCD inside the U.S., Corine in Europe and Australia, GeoCover LC otherwise.
6. Similar, although not identical, to the default WRF configuration chosen for the NEWA (Hahmann et al., 2020).
7. Point number 8, ERA5 documentation’s known issues, https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation#ERA5:datadocumentation-Knownissues

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