VALIDATION OF DIFFERENT CLIMATE REANALYSIS MODELS USING OBSERVATIONAL DATA AT SIX SITES IN MOROCCO

Younes ZEKEIK[1*], María José ORTIZ BEVIA[1] y Francisco José ALVAREZ-GARCIA[1]
[1]*Climate Physics Group, Department of Physics and Mathematics, University of Alcalá, Alcalá de Henares, Spain.*
younes.zekeik@edu.uah.es, mjose.ortiz@uah.es, franciscoj.alvarez@uah.es

RESUMEN
Los datos de viento reanalizados son valiosos para la planificación y la evaluación, especialmente cuando se carece de observaciones. Sin embargo, los productos de reanálisis de viento disponibles pueden diferir significativamente en algunas regiones donde los datos no están bien muestreados o donde los modelos utilizados no tienen habilidad predictiva, como es el caso de Marruecos. Este trabajo compara la variabilidad observada para los años 2015-2016 en seis lugares diferentes de Marruecos con la simulada por los datos de viento de los reanálisis ERA5-Land, JRA-55, MERRA-2 y NCEP/NCAR R1 en los mismos puntos y años. Se utilizan diferentes metodologías estadísticas lineales y no lineales para determinar la precisión y el potencial del reanálisis en esta región como alternativa o complemento a las observaciones realizadas in situ. Los resultados indican que, si bien el reanálisis representa de forma coherente las tendencias generales, las discrepancias varían según la localización geográfica y la estación del año. Los datos de viento de ERA5-Land obtienen los mejores resultados, mientras que los obtenidos por MERRA-2 se aproximan (con mejor rendimiento en las localizaciones del interior). El estudio subraya la importancia de la verificación local antes de utilizar el reanálisis en aplicaciones prácticas como la modelización climática o la planificación de recursos.

Palabras clave: Datos de reanálisis, Distribución de Weibull, Variabilidad interanual, Vacilaciones del viento.

ABSTRACT
Reanalysed wind data are valuable for planning and assessment, especially when wind observations are lacking. However, the available wind reanalysis products may differ significantly in some regions where the data are not well sampled or where the models used do not have predictive skills, which is the case of Morocco. This paper compares the observed variability for 2015-2016 at six locations in Morocco with the variability simulated by ERA5-Land, JRA-55, MERRA-2 and NCEP/NCAR R1 reanalysis wind data at the exact locations and years. Different linear and nonlinear statistical methodologies are used to determine the accuracy and potential of reanalysis at this region as an alternative or complement to observations made in situ. The results indicate that while reanalysis consistently represents overall trends, discrepancies vary by geographic location and season. The results of the ERA5-Land wind data

stand out, while those achieved by MERRA-2 are close (with better performance at inland locations). The study highlights the importance of local verification before using reanalysis in practical applications such as climate modelling or resource planning.

Keywords: Reanalysis data, Weibull distribution, Interannual variability, Wind vacillations.

1. INTRODUCTION

The climate of Morocco varies between semi-arid and arid, with complex spatial and temporal variations resulting from the diversity of the region's geography, influenced by both the Mediterranean Sea and the Atlantic Ocean. Winds play a crucial role in this climate system, with diverse air currents such as the regular trade winds on the Atlantic coasts and the warm Saharan winds known as "chergui". Inland, the winds are more turbulent and variable due to the Atlas Mountains' presence, further complicating wind behaviour. These conditions generate significant differences between coastal and inland areas and the country's northern and southern regions. Given the scarcity of in situ climate data in Morocco, climate reanalysis datasets constitute an essential complement by providing continuous records of meteorological variables using advanced numerical models. Among these datasets, ERA5, IFREMER, and ASCAT wind data have been successfully used in long-term assessments of wind potential in Morocco's marine and coastal areas (Zekeik et al., 2023; Benazzouz et al., 2021). However, reanalysis processes face significant challenges in areas of complex terrain, such as the Atlas Mountains, where the spatial resolution of models may not be sufficient to capture local wind characteristics accurately. Therefore, validating these data against local observations from ground-based meteorological stations is essential to assess their accuracy and applicability in Morocco. Improving the understanding of wind behaviour in Morocco by integrating reanalysis data and local observations is necessary for weather forecasting, energy resource management, and sustainable planning. This is particularly important for developing wind energy projects, water resource management, and agricultural planning, as well as contributing to climate change mitigation and promoting renewable energy use in the country.

2. DATA AND METHODS

2.1. Data Sets

2.1.a. Observed Wind Data

For the first site, Alkoudia-Albaida (AA), 10 min wind observations from 2016 from a wind farm mast are available 50 m and 80 m above the ground. For the second site, Dakhla (DK), the 1-hour observations were made with a meteorological station recording at two different heights, 50 m and 75 m, a device considered equivalent to the one used in mast observations. The estimated instrumental error of these measurements was ± 0.5 m/s. At the four remaining locations, 1-hour wind observations recorded at 10 m height by meteorological stations, retrieved from the Hadley Centre's Integrated Surface Database (HadISD) version 3.1.0.2019f (2020), were used. These data were quality-controlled to remove insufficient data and to keep the extremes (Dunn, 2019). Figure 1. a shows the positioning of the selected sites.

2.1.b. Reanalysed Wind Datasets

Four advanced, widely recognised global reanalyses were used in this study: ERA5-Land from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Copernicus Climate Change Service (C3S), 2019); the Japanese 55-year reanalysis (JRA-55), from the Japan Meteorological Agency (JMA) (Kobayashi et al., 2015), the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), from NASA (Gelaro et al., 2017), and the National Center for Environmental Prediction and National Center for Atmospheric Research Reanalysis (NCEP/NCAR R1) (Kalnay et al., 1996). These reanalyses were based on a comprehensive exploratory analysis, where other alternatives were also considered, including earlier versions of some datasets, such as JRA-25 (Onogi et al., 2007), ERA40 (Uppala et al., 2005), ERA-Interim (Dee et al., 2011) and MERRA (Molod et al., 2015). However, only NCEP/NCAR R1 was chosen over its more recent version, NCEP/DOE R2 (Kanamitsu et al., 2002), due to its superior performance in simulating the wind field in the study area.

The exploratory analysis also included regional reanalyses with higher spatial resolution, such as UERRA-HARMONIE (Ridal et al., 2017) and UERRA-MESCAN-SURFEX (Pelosi et al., 2020). These regional reanalyses generally improve global reanalyses obtained through dynamic downscaling and data assimilation techniques (Mesinger et al., 2006; Gleeson et al., 2017). However, since the performance of regional reanalyses depends mainly on the quality of the global products on which they are based (Ramon et al., 2019), it was decided to focus the analysis at this stage exclusively on global reanalyses, leaving the evaluation of regional wind energy simulations for future research.

2.2. Validation Methodologies

The first validation method of the wind reanalysis consisted of estimating basic statistical parameters, namely the Pearson correlation coefficient (CC) (Ranadip, 2017), the root mean square error (RMSE), the mean bias error (MBE), the standard deviation of the error (STDE), the coefficient of variance (Cv), and the coefficient of determination (R^2, given by one minus the ratio of the residual to the total sum of squares, as, for instance, in (Stetco et al., 2019).

The second validation method is based on fitting a statistical distribution to the observed and the reanalysed wind data and comparing the distribution parameters in each case. This method does not require the linearity hypothesis. Several statistical distributions have been applied to the study of the wind resource. Among them, the two parameters of Weibull distribution are the most frequently used for characterising wind speed at a specific location over a specified period (Carta et al., 2009). The Weibull probability density function is written as:

$$f(v) = \left(\frac{k}{c^*}\right)\left(\frac{v}{k}\right)^{k-1} exp\left[-\left(\frac{v}{c^*}\right)^k\right] \qquad (1)$$

The c^* (scale parameter, in m/s) is mainly proportional to the mean value of the wind speed, while the dimensionless coefficient k (shape parameter) is linked to the standard deviation.

Various methods for estimating the shape and scale parameters of the Weibull distribution are available in the literature, including the least square regression method, the non-iterative method, the method of moments, and the maximum likelihood method.
Among the methods mentioned, we chose to use the one-of-moment shape in this study because it is based on the average real daily wind speed and its daily standard deviation (Chauhan et al., 2014). The daily shape and scale parameters of the Weibull distribution function were calculated using:

$$c^* = \frac{\overline{v}}{\Gamma\left(1+\frac{1}{k}\right)}[m/s] \tag{2. a}$$

$$k = \left(\frac{\sigma}{\overline{v}}\right)^{-1.086} \tag{2. b}$$

Here, $\overline{v}$ and σ denote the time series' mean and standard deviation.
To validate the wind direction, its distribution was divided into sixteen segments of equal width, each with an extension of 22.5°, one for instance being North (N), followed by North-North-East (NNE), North-East (NE), East-North-East (ENE), East (E), East-South-East (ESE), South-East (SE), South-South-East (SSE), South (S) and so on. Thus, the frequencies of the wind direction distribution were calculated according to the following equation:

$$f_j = \frac{c_j}{\sum_1^j c_j} \tag{3}$$

where j is the index of the sector compass, c_j is the wind speed value assigned to sector j, and f_j is the occurrence frequency of the j directional wind.

3. RESULTS

3.1. Linear Validation

Figure 1 shows the difference in wind speed estimates at 10 m height between the Morocco region's four reanalyses (ERA5-Land, JRA-55, MERRA-2 and NCEP/NCAR-R1). JRA-55 and MERRA-2 have higher wind speeds (6-8 m/s) and a more homogeneous distribution, especially in the Atlantic coastal regions, which may reflect a higher sensitivity to large-scale synoptic phenomena or that these reanalyses tend to underestimate stronger winds compared to other winds. On the other hand, ERA5-Land and NCEP/NCAR-R1 show lower wind speeds, with more significant variation between coastal and continental regions, better capturing the influence of local topography. These differences underscore the importance of considering multiple reanalyses to obtain a complete picture of wind behaviour in long-term climate studies of the region.

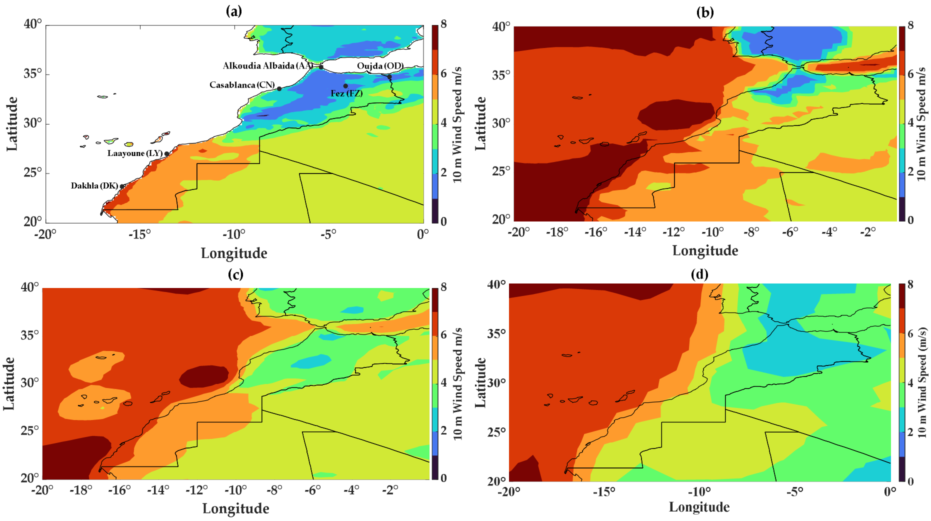

Fig. 1: Mean wind speed of the reanalysis wind data at 10 m height (m/s) for the validation period (2015–2016). (a) ERA5-Land data, (b) JRA-55 data, (c) MERRA-2 data and (d) NCEP/NCAR R1 data.

The previous figure compares statistical estimates of the mean, standard deviation, mean squared coefficient, and marginal standard deviation of each reanalysed wind field with the observations performed here. From this comparison, the winds produced by ERA5-Land and MERRA-2 appeared to have lower errors in the mean, standard deviation, marginal standard deviation, and marginal standard deviation. They also recorded higher R^2 correlations and CC correlation coefficients, which measure the degree of linearity between these two data sets. These results reflect that the winds simulated by ERA5-Land and MERRA-2 were in better agreement with the observed data. For example, wind speeds at 10 m altitude were significant at three of the studied sites but more critical at the southern site (DK), where the observation mean value of 6.86 m/s was well captured by the corresponding ERA5-Land mean value of 6.82 m/s. Similarly, at the northern position (AA), the mean value of 5.17 m/s derived from observations is equivalent to 4.99 m/s in ERA5-Land. Conversely, at the inland sites (OD and FZ), MERRA-2 outperforms ERA5-Land. Compared to ERA5-Land, MERRA-2, NCAR/NCEP R1, and JRA-55, winds recorded lower correlation values at all selected sites.

3.2. Non-linear Validation

Furthermore, as mentioned in the methodology, a second validation was performed based on comparing the modelled CDF and PDF and the Weibull PDF estimates from different wind speed datasets at the studied sites. From Figure 2, it appears that at the wind farm sites (AA and DK), the ERA5-Land and MERRA-2 wind data were closer to the Weibull CDF obtained from the real-time data than the other reanalysis wind data, with an advantage for ERA5-Land. At the inland sites (OD and FZ), the MERRA-2 wind performance was better at the station (CN); similarly, only at the station (LY) did neither of the reanalysed CDFs closely approach the observed CDF. This relatively weaker performance of NCEP/NCAR R1 and JRA-55 can be explained by their coarse spatial resolution (1° latitude × 1° longitude), which means a greater distance for the studied stations to the nearest grid point. The parameters c* and k were also calculated from the Weibull PDF, their confidence intervals at the 95% significance level and their variances, and we concluded that ERA5-Land gives the best estimate of c* at sites AA and DK. From the significant value of the shape parameter k at DK, it can be inferred that the winds at site DK were very regular and uniform. In contrast, the smaller values of k at site AA indicated winds that were variable in speed and stability. At the inland sites (OD and FZ), the parameter estimates of MERRA-2 were closer to the observations than those of ERA5-Land. The relatively poor performance of the reanalysed winds at LY can be linked to their failure to capture some significant outliers in the observations. The observed variability at the four northern sites was overestimated.

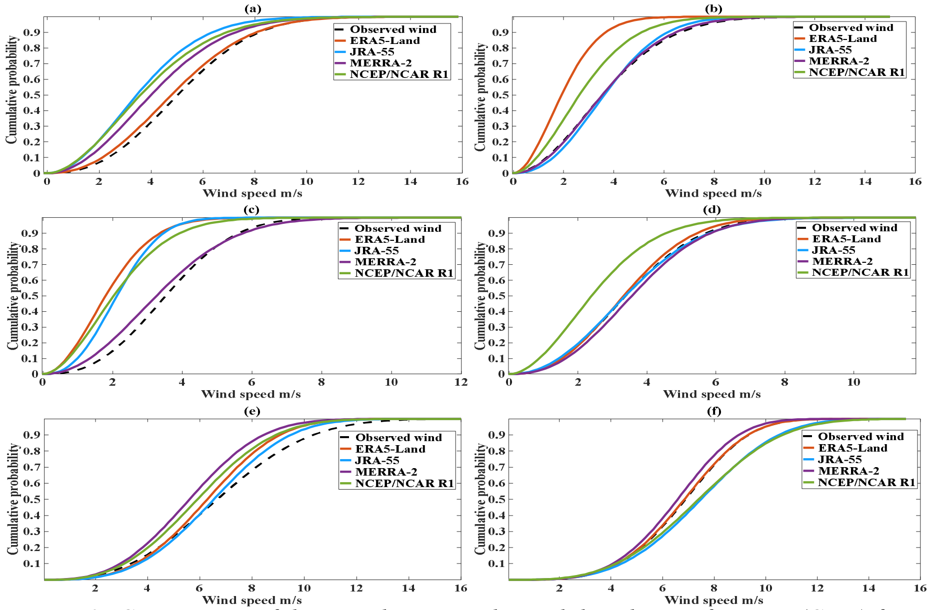

Fig. 2: Comparison of the cumulative wind speed distribution function (CDF) for the six locations. (a) Alkoudia Albaida, (b) Oujda, (c) Fez, (d) Casablanca, (e) Laayoune, (f) Dakhla.

3.3. Wind Direction Validation

The directional wind frequency analysis was included to obtain more quantitative results and validate the wind direction, as described in the Methodology section. Regarding the observed wind characteristics, the results of Figure 3 show that the winds are bimodal in (AA), while in (DK), the dominant directions were N, NNE and NE. The directional wind frequency in (LY) was similar to that in (DK). In contrast, the prevailing winds at the inland station (OD) shift from S to NNW, while in (FZ), the winds with an easterly component were less frequent. Finally, in the case of CN, the prevailing winds have a northerly component, as was the case in (DK) or (LY), but the frequency of the winds with a southerly component is not negligible. To validate the directional wind frequency, it can be estimated that the band representing the ERA5-Land reanalysis estimate was closest to one of the observations at almost all stations.

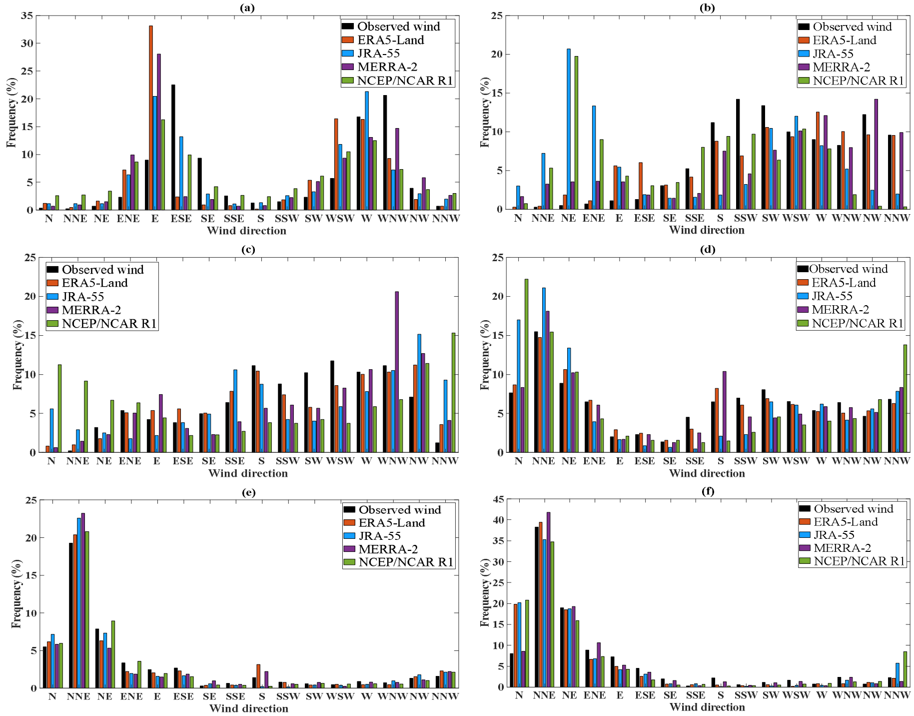

Fig. 3: Directional wind frequency obtained from observations (black), ERA5-Land (orange), JRA-55 (blue), MERRA2 (violet), NCEP/NCAR-R1 (green) for (a) Alkoudia Albaida, (b) Oujda, (c) Fez, (d) Casablanca, (e) Laayoune, (f) Dakhla. The year represented was 2016 at stations AA, OD, FZ, and CN, and 2015 at LY and DK.

3.4. Interannual Variability Validation

The monthly wind speeds at 10 m height obtained from observations were represented against those obtained from the reanalysis of wind data at the study sites (Figure 1). There was an essential consistency in the seasonal evolution of the winds at the AA site, with wind speeds ranging from 4.02 m/s to 6.33 m/s. Symmetries can also be estimated for the CN and LY cases. The seasonal variation was slight at the OD and FZ sites (approximately 3–4 m/s). This was not the case at DK, where wind speeds ranged from 4.56 m/s to 7.80 m/s. Differences in the behaviour of wind direction and speed between north and south were also found, as noted in previous studies (Knidiri et al., 1986; El Khchine et al., 2021). According to the classification proposed by the National Renewable Energy Laboratory (NREL), locations with wind speeds greater than 5 m/s at 10 m height are suitable for commercial-scale energy production (Bianchi et al., 2006). In the present study, both sites (AA and DK) had the advantage of average wind speeds exceeding the stated value, effectively giving them the potential for large-scale wind energy production. The average seasonal cycle obtained from five years of ERA5-Land reanalysis (including the year used for validation) at each of the selected stations is also represented in Figure 4. A comparison with the observed and reanalysed monthly values allows for a better understanding of the previous results. The ERA5-Land reanalysed winds outperformed the others at AA, LY and DK, and their performance at CN was similar. At the inland stations (OD and FZ), a gap can be observed between the monthly ERA5-Land estimates and the monthly observations and between the average ERA5-Land values and the latter, which could not be found in the case of the other reanalyses and highlights the relatively weaker performance of the ERA5-Land reanalysis in estimating wind speeds at those locations. This fact did not affect our results because the low average wind values at the two inland sites and other wind characteristics did not indicate these locations as the most promising locations for wind park construction.

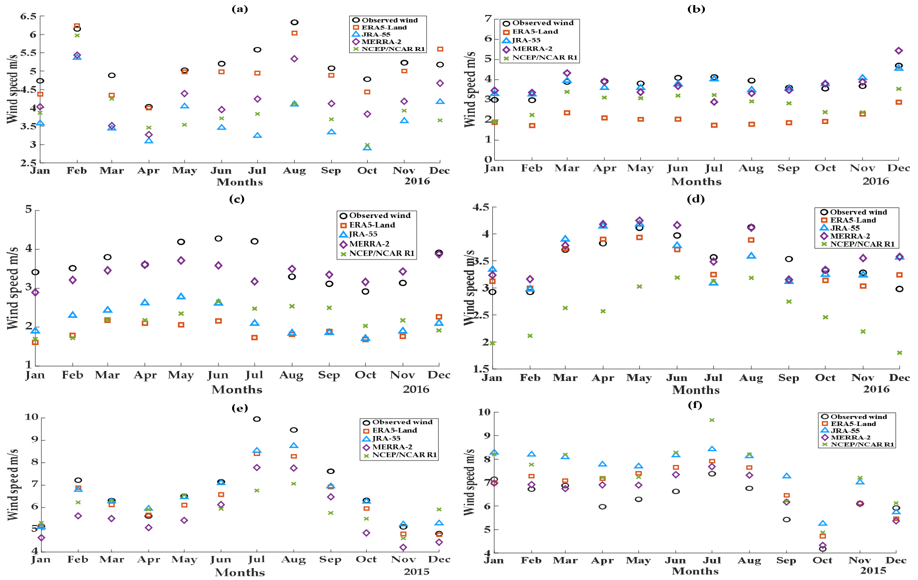

Fig. 4: Monthly wind values from observations (black circles), ERA5-Land (orange square), JRA-55 (blue triangle), MERRA-2 (violet diamond), NCEP/NCAR-R1 (green square) for (a) Alkoudia Albaida, (b) Oujda, (c) Fez, (d) Casablanca, (e) Laayoune, (f) Dakhla.

CONCLUSIONS

The time series corresponding to the six sites analysed in the reanalysis datasets were identified and validated against 10-m wind values obtained from mast observations and supplemented with 10-m meteorological wind data through linear and non-linear methodologies. The results of this study reveal that the wind fields re-analysed by ERA5-Land and MERRA-2 offer high spatial and temporal resolution, as evidenced by the parameters estimated from linear statistical validation techniques (RMSE, MBE, bias and R-squared (R^2)) as well as by non-linear probability density functions (PDF).

In particular, at site AA, the parameters determined from ERA5-Land are closer to those obtained from observations than the corresponding values of MERRA-2. This discrepancy is attributed to ERA5-Land's superior ability to resolve terrain complexity, which is critical in areas with variable topographic characteristics. At the DK site, the performance of the MERRA-2 reanalysis was similar to that of ERA5-Land, suggesting that MERRA-2 may provide competitive results under certain conditions.

At inland sites (OD and FZ), MERRA-2 and JRA-55 showed superior performance compared to ERA5-Land, indicating that the choice of reanalysis dataset can significantly affect the estimation of wind potential based on geographic location and characteristics from the terrain. The first three wind reanalyses provided similar results at the remaining sites (CN and LY), reinforcing the consistency of the data.

Regarding wind speeds at 10 m, the northern site (AA) showed mean values close to 5 m/s, with a dominant direction that varies seasonally from predominantly easterly to westerly. In contrast, the southern site (DK) recorded an average speed greater than 6.5 m/s, with northern wind directions dominating. While these values support the wind potential of both sites, they emphasise the suitability of the southern site for renewable energy development. The other southern site (LY), included in the validation, presented average values and wind potential similar to DK. Finally, sites OD and FZ showed average wind speeds below 4 m/s, indicating limitations on their suitability for wind projects.

In conclusion, this study contributes to a better understanding of wind dynamics in Morocco and provides essential information for the region's planning and development of wind energy projects. Validating reanalysis data against local observations is a crucial step to improving the management of energy resources and mitigating the challenges associated with climate change.

ACKNOWLEDGEMENTS

The author thanks the European Center for Medium-Range Weather Forecasts (ECMWF), Japan Meteorological Agency (JMA), National Center for Environmental Forecasting (NCEP)/National Center for Weather Forecast and Atmospheric Research (NCAR) for producing, making available and making use of data sets on a large scale. The Met Office Hadley Centre: National Centers for Environmental Information – NOAA are acknowledged for the HadISD dataset. Prof. A RuizdeElvira and Prof. JC Nieto-Borge are acknowledged for sharing their computer resources with us for this study. The Compagnie Eolienne du Detroit (CED)-Tangier and Prof. Youness El

Mourabit are recognised for providing the raw wind data. Additionally, A RuizdeElvira is thanked for their helpful comments.

REFERENCES

Benazzouz, A.; Mabchour, H.; El Had, K.; Zourarah, B.; Mordane, S. Offshore Wind Energy Resource in the Kingdom of Morocco: Assessment of the Seasonal Potential Variability Based on Satellite Data. J. Mar. Sci. Eng. 2021, 9, 31. https://doi.org/10.3390/jmse9010031.

Bianchi, F.D.; Mantz, R.J.; De Battista, H. Wind Turbine Control Systems: Principles, Modelling and Gain Scheduling Design; Springer Science & Business Media: London, UK, 2006.

Carta, J.A.; Ramírez, P.; Velázquez, S. A review of wind speed probability distributions used in wind energy analysis: Base studies in the Canary Islands. Renew. Sustain. Energy Rev. 2009, 13, 933-955. https://doi.org/10.1016/j.rser.2008.05.005.

Chauhan, A.; Saini, R.P. Statistical analysis of wind speed data using Weibull distribution parameters. In Proceedings of the 2014 1st International Conference on Non-Conventional Energy (ICONCE 2014), 2014, pp. 160-163. https://doi.org/10.1109/ICONCE.2014.6808712.

Copernicus Climate Change Service (C3S). C3S ERA5-Land reanalysis. Copernic Clim. Change Serv. 2019. https://cds.climate.copernicus.eu/cdsapp#!/home. (Accessed 23 July 2023).

Dee, D.P.; et al. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 2011, 137, 553-597. https://doi.org/10.1002/qj.828.

Dunn, R.J.H. Hadisd v3: Monthly updates. Hadley Centre Tech. Note 2019, 103.

El Khchine, Y.; Sriti, M. Performance evaluation of wind turbines for energy production in Morocco's coastal regions. Results Eng. 2021, 10, 100215. https://doi.org/10.1016/j.rineng.2021.100215.

Gelaro, R.; McCarty, W.; Suárez, M.J.; Todling, R.; Molod, A.; Takacs, L.; Randles, C.A.; Darmenov, A.; Bosilovich, M.G.; Reichle, R.; Wargan, K.; Coy, L.; Cullather, R.; Draper, C.; Akella, S.; Buchard, V.; Conaty, A.; da Silva, A.M.; Gu, W.; Kim, G.-K.; Koster, R.; Lucchesi, R.; Merkova, D.; Nielsen, J.E.; Partyka, G.; Pawson, S.; Putman, W.; Rienecker, M.; Schubert, S.D.; Sienkiewicz, M.; Zhao, B. The Modern-Era retrospective analysis for research and Applications, version 2 (MERRA-2). J. Clim. 2017, 30, 5419-5454. https://doi.org/10.1175/JCLI-D-16-0758.1.

Gleeson, E.; Whelan, E.; Hanley, J. Met Éireann high resolution reanalysis for Ireland. Adv. Sci. Res. 2017, 14, 49–61. https://doi.org/10.5194/asr-14-49-2017.

Kanamitsu, M.; Ebisuzaki, W.; Woollen, J.; Yang, S.; Hnilo, J.J.; Fiorino, M.; Potter, G.L. NCEP–DOE AMIP-II Reanalysis (R-2). Bull. Am. Meteorol. Soc. 2002, 83, 1631-1644. https://doi.org/10.1175/BAMS-83-11-1631.

Kalnay, E.; Kanamitsu, M.; Kistler, R.; Collins, W.; Deaven, D.; Gandin, L.; Iredell, M.; Saha, S.; White, G.; Woollen, J.; Zhu, Y.; Chelliah, M.; Ebisuzaki, W.; Higgins, W.; Janowiak, J.; Mo, K.C.; Ropelewski, C.; Wang, J.; Leetmaa, A.; Reynolds, R.; Jenne, R.; Joseph, D. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 1996, 77, 437-470. https://doi.org/10.1175/1520-0477(1996)077<0437>2.0.CO;2.

Kistler, R.; Kalnay, E.; Collins, W.; Saha, S.; White, G.; Woollen, J.; Chelliah, M.; Ebisuzaki, W.; Kanamitsu, M.; Kousky, V.; Van den Dool, H.; Jenne, R.; Fiorino, M. The NCEP–NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation. Bull. Am. Meteorol. Soc. 2001, 82, 247-268. https://doi.org/10.1175/1520-0477(2001)082<0247>2.3.CO;2.

Kobayashi, S.; Ota, Y.; Harada, Y.; Ebita, A.; Moriya, M.; Onoda, H.; Onogi, K.; Kamahori, H.; Kobayashi, C.; Endo, H.; Miyaoka, K.; Takahashi, K. The JRA-55 Reanalysis: General specification and basic characteristics. J. Meteorol. Soc. Jpn. 2015, 93, 5-48. https://doi.org/10.2151/jmsj.2015-001.

Knidiri, F.; Laaouina, A. L'énergie éolienne au Maroc: analyse préliminaire basée sur les données existantes, 1986, CDER. www.cder.org.ma.

Mesinger, F.; DiMego, G.; Kalnay, E.; Mitchell, K.; Shafran, P.C.; Ebisuzaki, W.; Jović, D.; Woollen, J.; Rogers, E.; Berbery, E.H.; Ek, M.B.; Fan, Y.; Grumbine, R.; Higgins, W.; Li, H.; Lin, Y.; Manikin, G.; Parrish, D.; Shi, W. North American Regional Reanalysis. Bull. Am. Meteorol. Soc. 2006, 87, 343-360. https://doi.org/10.1175/BAMS-87-3-343.

Met Office Hadley Centre & National Centers for Environmental Information - NOAA. (2020). HadISD: Global sub-daily, surface meteorological station data, 1931-2019, v3.1.0.2019f. Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/e488dccd09e1446d90978b75036475e2 (Accessed 29 April 2023).

Molod, A. et al. Development of the GEOS-5 atmospheric general circulation model: Evolution from MERRA to MERRA2. Geosci. Model Dev. 2015, 8, 1339-1356. https://doi.org/10.5194/gmd-8-1339-2015.

National Renewable Energy Laboratory (NREL). Home Page | NREL, n.d. https://www.nrel.gov/ (Accessed 20 November 2023).

Onogi, K. et al. The JRA-25 reanalysis. J. Meteor. Soc. Jpn. 2007, 85, 369-432. https://doi.org/10.2151/jmsj.85.369.

Pelosi, A.; Terribile, F.; D'Urso, G.; Chirico, G.B. Comparison of ERA5-Land and UERRA MESCAN-SURFEX Reanalysis Data with Spatially Interpolated Weather Observations for the Regional Assessment of Reference Evapotranspiration. Water 2020, 12, 1669. https://doi.org/10.3390/w12061669.

Ranadip, P. Chapter 4 - Validation methodologies. In Predictive Modeling of Drug Sensitivity; Pal, R., Ed.; Academic Press: 2017; pp. 83-107. https://doi.org/10.1016/B978-0-12-805274-7.00004-X.

Ramon, J.; Lledó, L.; Torralba, V.; Soret, A.; Doblas-Reyes, F.J. What global reanalysis best represents near-surface winds? Q. J. R. Meteorol. Soc. 2019, 145, 3236-3251. https://doi.org/10.1002/qj.3616.

Ridal, M.; Olsson, E.; Unden, P.; Zimmermann, K.; Ohlsson, A. Uncertainties in Ensembles of Regional Re-Analyses - Deliverable D2.7 HARMONIE reanalysis report of results and dataset (2017).

Stetco, A.; Dinmohammadi, F.; Zhao, X.; Robu, V.; Flynn, D.; Barnes, M.; Keane, J.; Nenadic, G. Machine learning methods for wind turbine condition monitoring: A review. Renew. Energy 2019, 133, 620-635. https://doi.org/10.1016/j.renene.2018.10.047.

Uppala, S. M., et al. (2005). The ERA-40 re-analysis. Quarterly Journal of the Royal Meteorological Society, 131(613), 2961-3012. https://doi.org/10.1256/qj.04.176.

Zekeik, Y., Ortiz-Bevia, M. J., Alvarez-Garcia, F. J., Haddi, A., El Mourabit, Y., & Ruiz-de-Elvira, A. (2024). Long-Term Assessment of Morocco’s Offshore Wind Energy Potential Using ERA5 and IFREMER Wind Data. Journal of Marine Science and Engineering, 12(3), 460. https://doi.org/10.3390/jmse12030460.