ANÁLISIS ESPECTRAL DE LA VELOCIDAD DEL VIENTO CERCA DE LA SUPERFICIE Y POSIBLES FUENTES DE PREDICTIBILIDAD EN LA PENÍNSULA IBÉRICA

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RESUMEN

Este estudio analiza en el dominio de la frecuencia series temporales observadas de la velocidad media del viento cerca de la superficie y de las rachas máximas diarias en la Península Ibérica. El objetivo principal será explorar posibles fuentes de predictibilidad a medio-largo plazo para estas variables en la región. La densidad espectral de potencia se estima a partir del método multitaper obteniendo que el comportamiento es caótico para periodos inferiores al año y cuasiperiódico para periodos superiores a los dos años, lo que justifica la posibilidad de encontrar fuentes de predictibilidad. Por otro lado, la transformada continua wavelet permite determinar comportamientos no estacionarios en las series analizadas, localizando en el tiempo las oscilaciones de mayor importancia. Por último, se calculará la coherencia wavelet entre ambas variables de viento y diversos modos de variabilidad océano-atmósfera que pueden estar relacionados con la velocidad del viento en la región como son: El Niño-Oscilación del Sur, la Oscilación del Atlántico Norte, La Oscilación del Mediterráneo Occidental o, debido a la influencia de los calentamientos súbitos estratosféricos en la troposfera peninsular, el vórtice polar estratosférico. El resultado principal es la alta correlación estadísticamente significativa entre las variables de viento y el vórtice polar para periodos cercanos al año con un desfase temporal de en torno a 2-3 meses con respecto a la antifase, es decir, una correlación negativa en la que el vórtice polar modula la velocidad del viento en la región con dicho desfase. Este trabajo puede tener aplicaciones directas en áreas como: la generación de energía eólica, la agricultura, la calidad del aire, los seguros y las industrias pesqueras, entre otros ámbitos.

Palabras clave: velocidad del viento, rachas máximas, análisis multitaper, análisis Wavelet, Península Ibérica.

ABSTRACT

This study analyzes in the frequency domain observed time series of mean near-surface wind speed and daily peak wind gusts over the Iberian Peninsula. The main objective will be to explore possible sources of predictability in the medium-long term for these variables in the region. The spectral power density is estimated from the multitaper method, the spectrum shows that the behaviour is chaotic for periods shorter than one year and quasi-periodic for periods longer than two years, which justifies the possibility of finding sources of predictability. Furthermore, the continuous wavelet transform allows us to determine non-stationary behaviour in the analyzed series, locating the most important oscillations in time. Finally, wavelet coherence will be calculated between both wind variables and various modes of ocean-atmosphere variability that may be related to wind speed in the region, such as: El Niño-Southern Oscillation, North Atlantic Oscillation, Western Mediterranean Oscillation or, the stratospheric polar vortex due to the influence of stratospheric sudden warmings in the peninsular troposphere. The main result is the high statistically significant correlation between wind variables and the polar vortex for periods close to the year with a time lag of about 2-3 months with respect to the antiphase, i.e., a negative correlation in which the polar vortex modulates the wind speed in the region with such a lag. This work may have direct applications in areas such as: wind power generation, agriculture, air quality, insurance and fishing industries, among others.

Key words: wind speed, wind gusts, variability modes, multitaper analysis, wavelet analysis, Iberian Peninsula.

1. INTRODUCTION

Although near-surface wind speed and wind gusts have not been studied as much as temperature or precipitation in the context of climate change (IPCC 2013), in recent years numerous studies have analysed these variables in the time domain, calculating their trends and correlations with different climate indices at various time scales (e.g., McVicar et al. 2012; Wu et al. 2018); this has also been the case for the Iberian Peninsula (IP, Azorin-Molina et al. 2014, 2016; Utrabo-Carazo et al. 2022). However, there are few scientific articles in the literature that analyse these atmospheric variables in the frequency domain despite all the information that can be gained from it (Grinsted et al. 2004). The characteristics of the spectrum of the variable to be considered allow us to recognize whether it is possible the existence of sources of predictability for this variable or if, on the contrary, its behaviour is chaotic (Serykh and Sonechkin 2019). Furthermore, techniques based on wavelets can be used to locate the main oscillations in time, allowing us to recognize non-stationary behaviour. These techniques have been successfully applied to different climatic variables such as precipitation or temperature (e.g., Penalba and Vargas 2004; Polanco-Martínez et al. 2020). However, to the authors' knowledge, they have only been applied once to surface wind with interesting results (Naizghi and Ouarda 2017). Being non-linear and non-stationary, wavelets allow us to perceive more features than classical linear analysis, such as tendences or Pearson correlation (Mares et al. 2021). The overall aim of this research is to apply for the first time in the Iberian Peninsula these techniques for near-surface mean wind speed and gusts. More specifically, particular objectives of this study are:

1. To estimate the power spectral density of the mean near-surface wind speed and wind gusts across the Iberian Peninsula.

2. To explore possible sources of predictability for these variables across this region. Section 2 covers a description of the data and analysis methods used; section 3 presents the results; section 4 discusses the principal findings against the state-of-the-art; and lastly, section 5 highlights the principal conclusions
and future perspectives this research.

2. DATA AND METHODS

2.1. Data

The wind data correspond to two quality-controlled and homogenized wind datasets whose characteristics are described in Utrabo-Carazo et al. 2022, one for the monthly mean near-surface wind speed (SWS) and the other for the daily peak wind gust (DPWG). Both come from 87 meteorological stations distributed over the IP, comprising the 59-yr 1961-2019 period. From these two sets of observed data, the two wind variables used in this study were calculated: the monthly mean wind speed anomaly (SWS anomaly) and the monthly mean daily peak wind gust anomaly (DPWG anomaly). Defining the climatology as the period from 1980 to 2010.
The zonal component of wind at 60ºN and at the 10hPa level (hereinafter Polar vortex) is selected from the ERA5 reanalysis (available online at https://www.ecmwf.int/en/forecasts/datasets/reanalysisdatasets/era5; last accessed April 10, 2020). It is chosen as a representation of the state of the stratospheric polar vortex (Charlton and Polvani 2007).
The Niño 3.4 SST Index (Niño 3.4) is retrieved from the National Oceanic and Atmospheric Administration (NOAA; available online at https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34; last accessed April 10, 2020). It is chosen due to ENSO influence on the North Atlantic region (Rodríguez-Fonseca et al. 2016).
The North Atlantic Oscillation index (NAOi; available online at https://crudata.uea.ac.uk/cru/data/nao/; last accessed April 10, 2020) and the Western Mediterranean Oscillation index (WeMOi; available online at http://www.ub.edu/gc/es/wemo/; last accessed April 10, 2020) are chosen due to their proven high correlation with the above wind variables, negative for NAOi and positive for WeMOi (Utrabo-Carazo et al. 2022).

2.2. Methods

We obtain the power spectral density of the DPWG anomalies through the multitaper method (Thomson 1982) using the matlab toolbox "jLab" (available online at http://jmlilly.net/software.html; last accessed April 10, 2022). This technique gives us a better estimation of the spectrum compared to the conventional Fourier analysis since multiple independent estimates of the spectrum are obtained from the same sample (Bronez 1992; Percival and Walden 1993).
The wavelet analysis is performed through the matlab toolbox "Cross wavelet and wavelet coherence" (available online at https://github.com/grinsted/wavelet-coherence; last accessed April 10, 2022). We will compute: (1) the Continuous Wavelet transform (CWT) of each variable defined above, and (2) the Wavelet

Coherence (WC) between the wind variables and the rest of the parameters. Our choice is the Morlet wavelet with six as the dimensionless frequency. For more information about wavelet analysis see Grinsted et al. (2004) and the references therein.

3. RESULTS

The features of the spectrum obtained by the multitaper method indicate that the wind gusts behaviour is chaotic for periods of less than one year and quasi-periodic for periods longer than two years (Figure 1), similar behaviours are found for the rest of the variables (not shown). This result reinforces the possibility of obtaining predictability sources for these variables at these scales (Serykh and Sonechkin 2019).

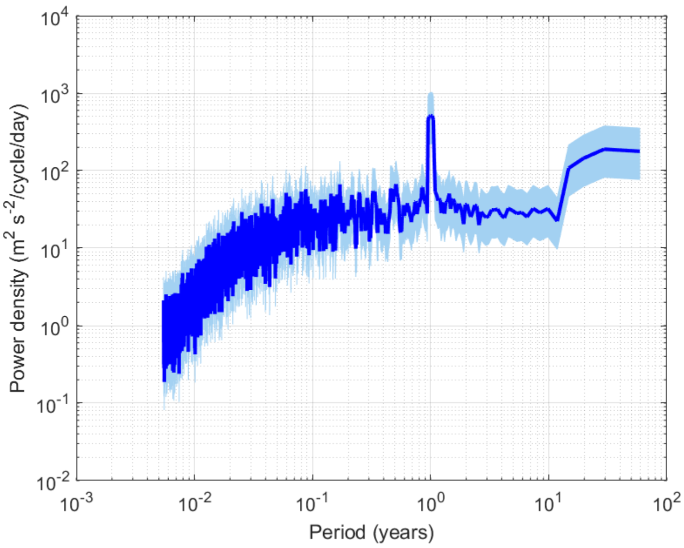

Fig. 1: DPWG anomalies spectrum from multitaper analysis. The light blue region shows the 95% confidence interval of the spectrum.

The CWT of the different variables are shown in Figure 2. The results for the SWS anomalies (a) and for the DPWG anomalies (b) show quite similarity. The most powerful and statistically significant regions are located in periods between 8 and 16 months, although there are non-significant regions with high relative power for longer periods. As for the previous variables, the polar vortex (c) concentrates all its significant power in the periods between 8 and 16 months, but unlike before, no other regions with high relative power are found. In contrast to the previous cases, Niño 3.4 shows a high generalized power in all periods longer than approximately 12 months, with the statistically significant region concentrated between 12 and 64 months. Finally, the results for NAOi and WeMOi show a greater temporal discontinuity, with the regions with the highest power concentrated at certain points in time. For NAOi, there is a statistically significant region around 2011 with periods between 16 and 32 months, and a region with a period longer than 128 months starting around 1994. For the WeMOi, there is a significant region for periods longer than 130 months, but the series is too short and most of it falls within the COI, and there is also a significant region between 1994 and 2008 for periods close to 120 months.

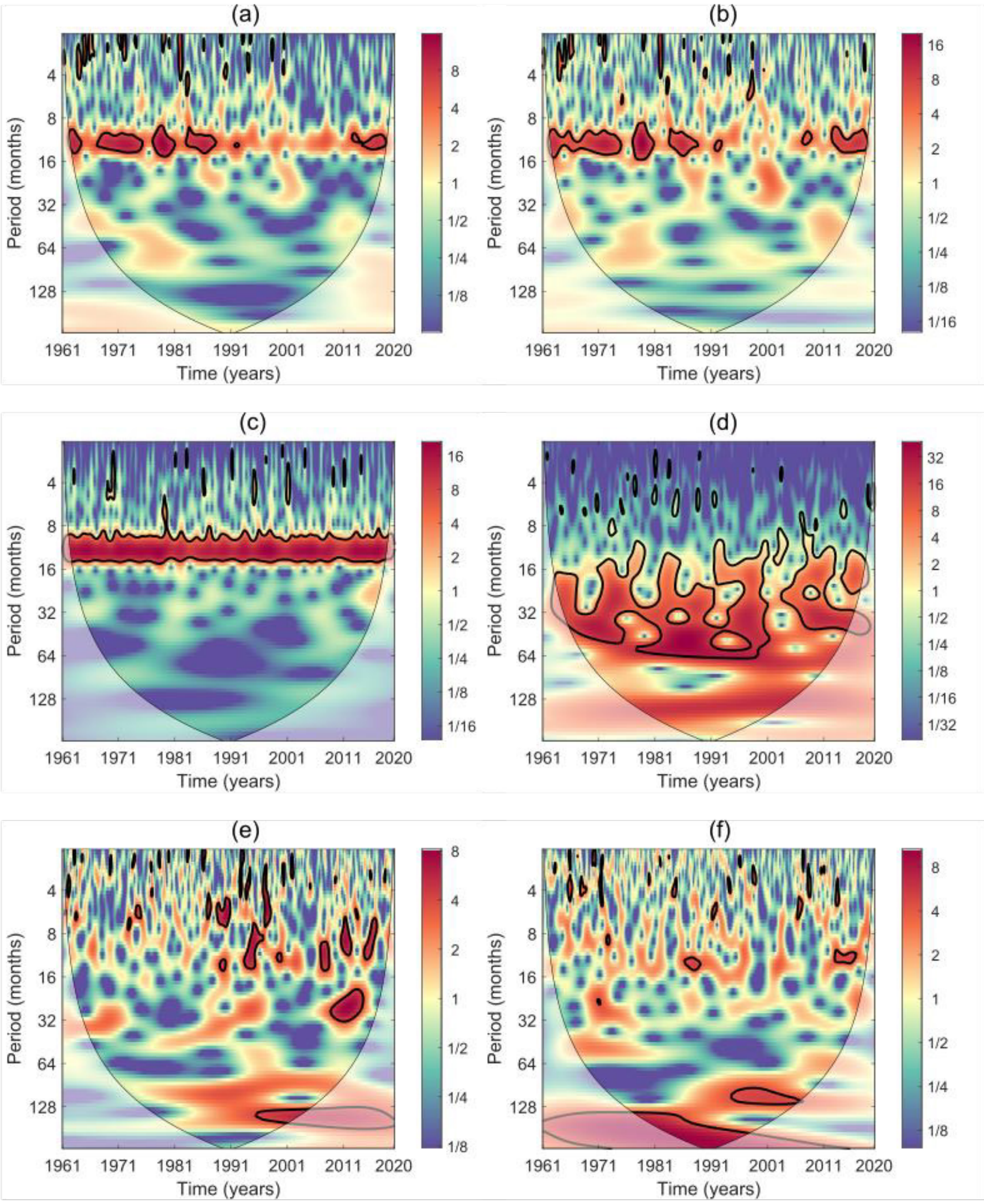

Fig. 2: Continuous Wavelet Transform of: (a) SWS anomalies, (b) DPWG anomalies, (c) Polar vortex, (d) Niño 3.4, (e) NAOi and (f) WeMOi. The thick black contour designates the significant regions against red noise (p < 0.05) and the cones of influence (COI) where edge effects might distort the results are shown as a lighter shade.

Looking at the Wavelet Coherence between both wind variables and the rest of the parameters, Figure 3 for SWS anomalies and Figure 4 for DPWG anomalies. The most outstanding result corresponds to the high correlation between the polar vortex and the mean SWS and gust anomalies for periods ranging from 8 to 16 months with an approximate relative phase of 60º with respect to the antiphase. That means when the polar vortex is weak, we have strong winds on the peninsula about two months later, and the other way around with a strong polar vortex and weak winds. This would agree with what we know about stratospheric sudden warmings (SSW) and their effects on the troposphere, since an SSW with a tropospheric signal would translate into a negative NAO (Hall et al. 2021), which as we have already mentioned correlates negatively with near-surface mean wind speed and gusts over the Iberian Peninsula. Other interesting signals among these variables are found in the periods between 70 and 100 months, being significant and approximately in phase at the beginning of the series between 1961 and 1981.
Another interesting result is the disconnection between mean SWS and gust anomalies for periods between 9 to 11 years, for which we have not yet found any plausible explanation. For the rest of the periods the correlation is significant, high and in phase as we would expect for these two variables.
On the other hand, the correlations between the wind variables and the rest of the indices (i.e., Niño 3.4, NAOi and WeMOi) show a behaviour closer to non-stationary, i.e., the main statistically significant signals are localized in time. In the case of NAOi, the correlation observed between 1991 and 2011 around the frequency of 64 months for both SWS and DPWG anomalies is noteworthy. For El Niño 3.4, the highest and significant correlations are found in two period bands, 16-32 months and 64-100 approximately, and in two time periods, 1961-1976 and 2001-2019, with the former being of greater magnitude for SWS anomalies and the latter for DPWG anomalies. A good part of these bands would be within the COI, so their reliability would not be high. Finally, the correlations with WeMOi are the most extensive among these three modes of climate variability, which could be expected given the high linear correlation with wind speed in the region on an annual scale (Utrabo-Carazo et al., 2022). They are distributed in patches between 8 and 128 months and during the entire time interval. The region between 64 and 100 months from 2001 onwards stands out, which could be related to that observed in the case of Niño 3.4, being again of greater extension for the DPWG anomalies.
Next steps will be to analyse the influence of other phenomena such as the quasi-biennial oscillation or the AMOC, and to determine the mechanisms that generate the relationships obtained here. Moreover, these techniques could be applied in a multivariate manner (Polanco-Martínez et al. 2020), on a seasonal scale or even by applying bandpass filters to increase the signal-to-noise ratio at the desired frequencies (Mares et al. 2021). Longer time series would be very useful as they would allow to detect interesting signals in the long term. These results may have great impact in agriculture, air quality, insurance and fishing industries, and especially in the wind energy industry since it would allow to predict the power generated by wind farms in the region in the medium-long term.

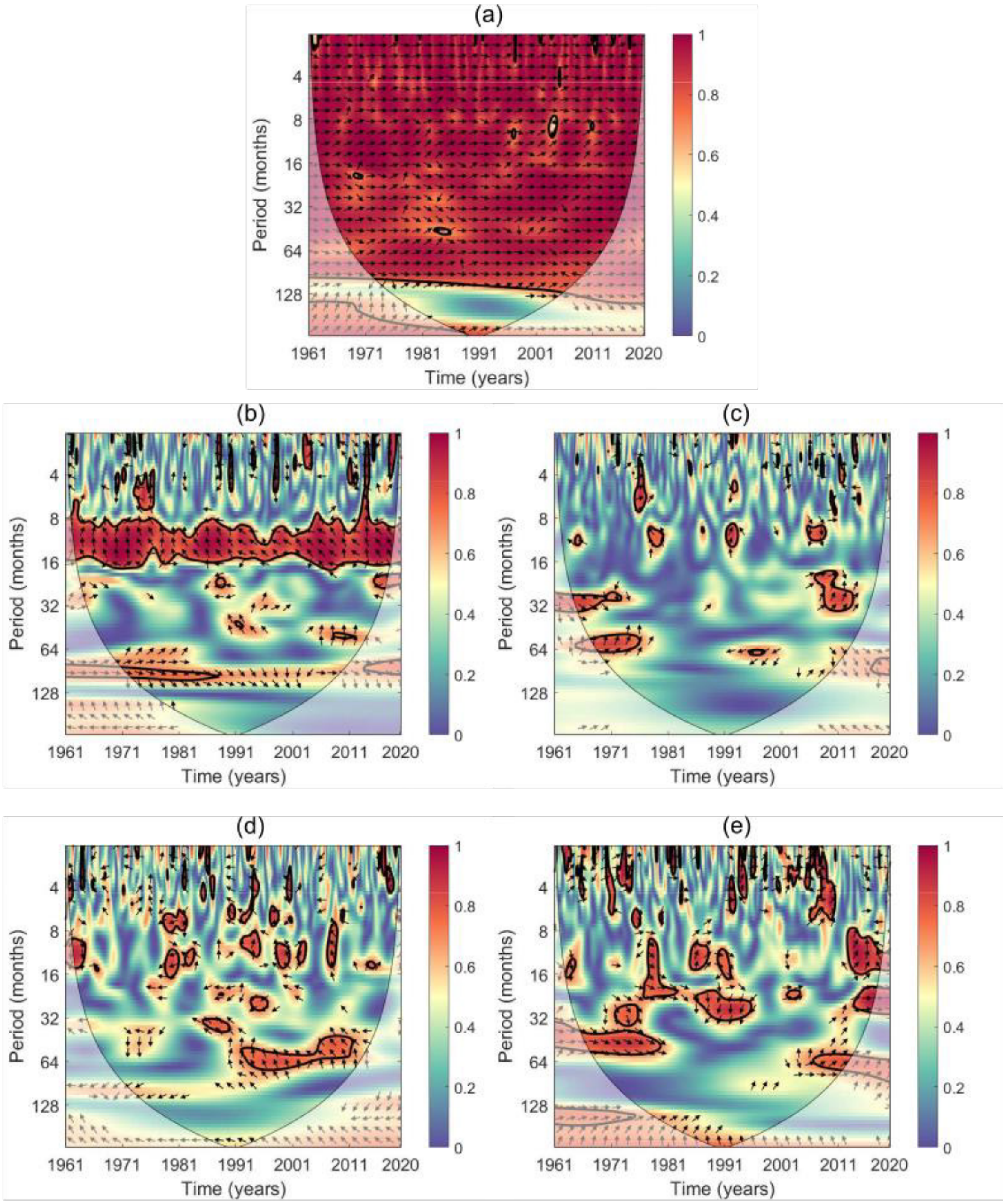

Fig. 3: Wavelet Coherence between SWS anomalies and: (a) DPWG anomalies, (b) Polar vortex, (c) Niño 3.4, (d) NAOi and (e) WeMOi. The thick black contour designates the significant regions against red noise (p < 0.05) and the cones of influence (COI) where edge effects might distort the results are shown as a lighter shade. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left, and SWS anomalies leading the other variable by 90º pointing straight down).

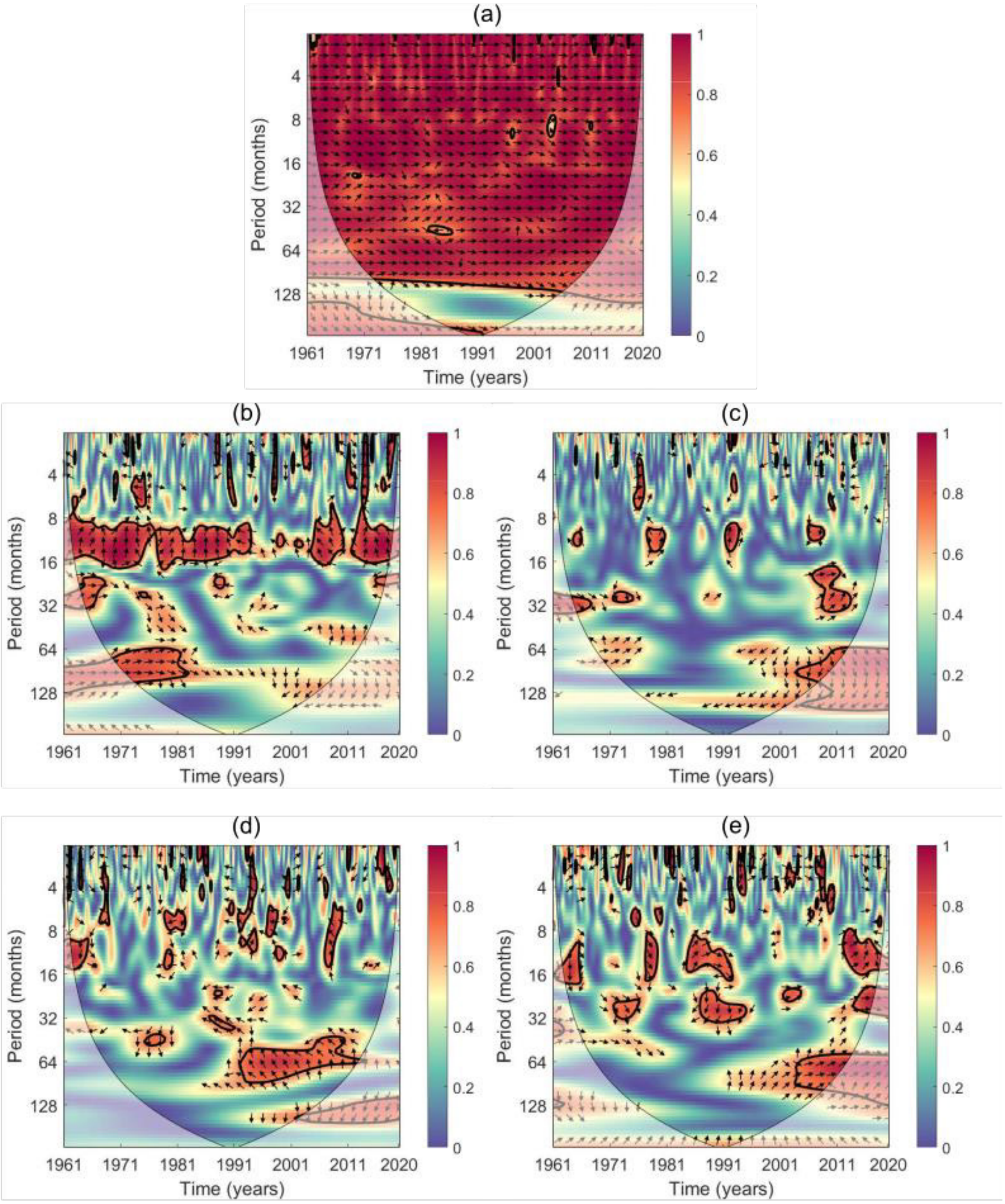

Fig. 4: Wavelet Coherence between DPWG anomalies and: (a) SWS anomalies, (b) Polar vortex, (c) Niño 3.4, (d) NAOi and (e) WeMOi. The thick black contour designates the significant regions against red noise ($p < 0.05$) and the cones of influence (COI) where edge effects might distort the results are shown as a lighter shade. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left, and DPWG anomalies leading the other variable by 90º pointing straight down).

4. CONCLUSIONS

The principal findings of this research focused on the Iberian Peninsula are:

- From multitaper analysis of observed daily peak wind gust (DPWG) anomalies we find that its behaviour is deterministic chaos for periods of less than 1 year and quasi-periodic for periods longer than 2 years. This justifies the possibility of finding sources of predictability for these longer periods.
- From the continuous wavelet transform we can locate the most important oscillations in time. In the case of the wind and polar vortex (represented through the zonal component of wind at 60ºN and at the 10hPa level) variables, they are concentrated in periods around the year, while for Niño 3.4 index they are distributed between the range 12-64 months. The North Atlantic Oscillation index (NAOi) and Western Mediterranean Oscillation index (WeMOi) show a non-stationary behaviour.
- From wavelet coherence analysis we find that there is a high and significant correlation between the stratospheric polar vortex and the near-surface mean wind speed (SWS) and DPWG anomalies in periods close to the year, with a time lag of 2-3 months with respect to the antiphase, that is polar vortex driving wind speed with a negative correlation.
- Non-stationary behaviour in the wavelet coherence between the wind variables and the Niño 3.4, NAOi and WeMOi. The correlation between wind variables and El Niño 3.4 and WeMOi in the periods between 64 and 100 months from 2001 onwards stands out, especially for the case of DPWG anomalies.
- Decoupling between mean SWS anomalies and DPWG anomalies for periods between 9 and 11 years. Significant, high and in phase correlation for the rest of the periods.

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REFERENCES

Azorin-Molina, C., Guijarro, J.A., McVicar, T.R., Vicente-Serrano, S.M., Chen, D., Jerez, S., and Espirito-Santo, F. (2016). Trends of daily peak wind gusts in Spain and Portugal, 1961-2014. J. Geophys. Res. Atmos., 121, 1059-1078. doi: https://doi.org/10.1002/2015JD024485

Azorin-Molina, C., and Coauthors (2014). Homogenization and assessment of observed near-surface wind speed trends over Spain and Portugal, 1961-2011. J. Clim., 27, 3692-3712. doi: https://doi.org/10.1175/JCLI-D-13-00652.1

Bronez, T. (1992). On the performance advantage of multitaper spectral analysis. IEEE Trans. Signal Process, 40 (12), 2941-2946.
doi: https://doi.org/10.1109/78.175738

Charlton, A. J., and Polvani, L. M. (2007): A new look at stratospheric sudden warmings. part I: Climatology and modeling benchmarks. J. Clim., 20 (3), 449–469. doi: https://doi.org/10.1175/JCLI3996.1

Grinsted, A., Moore, J.C., and Jevrejeva, S. (2004). Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlin. Processes Geophys., 11, 561-566.
doi: https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2

Hall, R.J., Mitchell, D.M., Seviour, W.J.M., and Wright, C.J. (2021). Tracking the Stratosphere-to-Surface Impact of Sudden Stratospheric Warmings. J. Geophys. Res. Atmos., 126, e2020JD033881. doi: https://doi.org/10.1029/2020JD033881

IPCC (2013). Climate change 2013: The physical science basis. Cambridge university press, 1535 pp. doi: https://doi.org/10.1017/CBO9781107415324

Mares, I., Dobrica, V., Mare, C., and Demetrescu, C. (2021): Assessing the solar variability signature in climate variables by information theory and wavelet coherence. Sci. Rep., 11, 11337. doi: https://doi.org/10.1038/s41598-021-90044-6.

McVicar, T.R., and Coauthors (2012). Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. J. Hydrol., 416-417, 182-205. doi: https://doi.org/10.1016/j.jhydrol.2011.10.024

Naizghi, M. S., and Ouarda, T. B. M. J. (2017): Teleconnections and analysis of long-term wind speed variability in the UAE. Int. J. Climatol., 37 (1), 230–248.
doi: https://doi.org/10.1002/joc.4700

Penalba, O. C., and Vargas, W. M. (2004): Interdecadal and interannual variations of annual and extreme precipitation over central north-eastern Argentina. Int. J. Climatol., 24 (12), 1565–1580. doi: https://doi.org/10.1002/joc.1069

Percival, D.B., Walden, A.T. (1993). Spectral analysis for physical applications. Cambridge university press. doi: https://doi.org/10.1017/CBO9780511622762.

Polanco-Martínez, J. M., Fernández-Macho J., and Medina-Elizalde, M. (2020). Dynamic wavelet correlation analysis for multivariate climate time series. Sci. Rep., 10 (21277). doi: https://doi.org/10.1038/s41598-020-77767-8

Rodríguez-Fonseca, B., and Coauthors (2016): A review of ENSO influence on the North Atlantic. A non-stationary signal. Atmosphere, 7 (7).
doi: https://doi.org/10.3390/atmos7070087

Serykh, I.V., and Sonechkin, D.M. (2019). Nonchaotic and globally synchronized short-term climatic variations and their origin. Theor. Appl. Climatol., 137, 2639-2656. doi: https://doi.org/10.1007/s00704-018-02761-0

Thomson, D. (1982). Spectrum estimation and harmonic analysis. Proc. IEEE, 70(9), 1055-1096. doi: https://doi.org/10.1109/PROC.1982.12433

Utrabo-Carazo, E., Azorin-Molina, C., Serrano, E., Aguilar, E., Brunet, M., and Guijarro, J.A. (2022). Wind stilling ceased in the Iberian Peninsula since the 2000s. Atmos. Res. doi: https://doi.org/10.1016/j.atmosres.2022.106153

Wu, J., Zha, J., Zhao, D., and Yang, Q. (2018). Changes in terrestrial near-surface wind speed and their possible causes: an overview. Clim. Dyn., 51, 2039-2078. doi: https://doi.org/10.1007/s00382-017-3997-y