



# The added value of simulated near-surface wind speed over the Alps from a km-scale multimodel ensemble

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## Abstract

The advancement of computational resources has allowed researchers to run convection-permitting regional climate model (CPRCM) simulations. A pioneering effort promoting a multimodel ensemble of such simulations is the CORDEX Flagship Pilot Studies (FPS) on “Convective Phenomena over Europe and the Mediterranean” over an extended Alps region. In this study, the Distribution Added Value metric is used to determine the improvement of the representation of all available FPS hindcast simulations for the daily mean near-surface wind speed. The analysis is performed on normalized empirical probability distributions and considers station observation data as the reference. The use of a normalized metric allows for spatial comparison among the different regions (coast and inland), altitudes and seasons. This approach permits a direct assessment of the added value between the CPRCM simulations against their global driving reanalysis (ERA-Interim) and respective coarser resolution regional model counterparts. In general, the results show that CPRCMs add value to their global driving reanalysis or forcing regional model, due to better-resolved topography or through better representation of ocean-land contrasts. However, the nature and magnitude of the improvement in the wind speed representation vary depending on the model, the season, the altitude, or the region. Among seasons, the improvement is usually larger in summer than winter. CPRCMs generally display gains at low and medium-range altitudes. In addition, despite some shortcomings in comparison to ERA-Interim, which can be attributed to the assimilation of wind observations on the coast, the CPRCMs outperform the coarser regional climate models, both along the coast and inland.

**Keywords** Regional climate modelling · Wind speed · Added value · Probability density functions · Downscaling

## 1 Introduction

Regional climate models (RCMs) allow the dynamic downscaling of global climate models (GCMs) with the aim of providing information on finer scales that are more suitable for studies of regional to local phenomena and assessments studies of impact, vulnerability and adaptation (Laprise 2008; Giorgi 2019). The GCMs can describe the response of the global circulation to large-scale forcing. At the same time, the RCMs can refine this large-scale information spatially and temporally by better taking into account the effects of forcing and processes that arise at finer scales, such as coastlines, topography or land use. Following this concept, convection-permitting RCMs (CPRCMs, Coppola et al.

(2020); Ban et al. (2021); Pichelli et al. (2021)) are model simulations performed at higher resolutions (horizontal grid spacing <4 km) compared to standard RCM (horizontal grid spacing >10 km) that represent regional to local scale processes in a more reliable way, due to a more accurate representation of topography (Kendon et al. 2012; Gutowski et al. 2020) and explicitly resolved deep convection (Prein et al. 2015; Weisman et al. 1997). The explicit representation of convective processes, instead of their parametrization when resolution is coarser, holds the key to enhancing the understanding and representation of the interconnected processes and variables (Berthou et al. 2020), including precipitation (Fumière et al. 2020; Knist et al. 2020; Caillaud et al. 2021), complex orographic mechanisms (Bauer et al. 2011; Pontopidan et al. 2017), regional weather extremes (Mass et al. 2002; Prein et al. 2015), the diurnal temperature cycle (Ban

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et al. 2021), near-surface wind patterns (Belušić Vozila et al. 2023), and land-atmosphere interactions (Knist et al. 2020; Barlage et al. 2021). Advancing the knowledge of deep convection can add valuable insights into these associated phenomena, leading to more accurate modelling and prediction of weather and climate.

Due to their computational cost, CPRCMs are commonly first tested over a smaller area (Knote and Heinemann 2010; Rasmussen et al. 2011). Extensive investigations have been conducted across various regions worldwide, spanning different seasons and time scales, ranging from decadal to climate-scale analyses (Leutwyler et al. 2017; Schär et al. 2020; Schwitalla et al. 2020). In particular, the Flagship Pilot Study about convective phenomena at high resolution over the Euro-Mediterranean region (FPSCONV, (Coppola et al. 2020; Ban et al. 2021; Pichelli et al. 2021), related to Euro-CORDEX (Jacob et al. 2020) and Med-CORDEX (Somot et al. 2018) initiatives, is a pioneering study about CPRCMs ensemble conducted in the framework of CORDEX (<https://cordex.org/experiment-guidelines/flagship-pilot-studies/endorsed-cordex-flagship-pilote-studies/europe-mediterranean-convective-phenomena-at-high-resolution-over-europe-and-the-mediterranean/>) that seeks to develop the first ensemble of climate convection-permitting simulations across Europe and the Mediterranean. Several studies in the literature have shown that increased horizontal resolution generally improves the representation of fine-scale processes, particularly relevant in complex terrain areas, as they better simulate topographic forcing Torma et al. (2015); Pontoppidan et al. (2017); Careto et al. (2021); Pichelli et al. (2021); Sangelantoni et al. (2022); Soares et al. (2022). Thus, the FPSCONV project was developed for the Alpine domain and presents the challenge of the quantitative assessment of the added value of regional downscaling at km-scale over Central Europe. The greater Alpine region was chosen due to its complex orography, proximity to the Mediterranean Sea and vulnerability to extreme events, which can exhibit complex atmospheric and climatic patterns, and could be better represented by a larger spatial resolution. The region is also a well-known climate change hotspot, meaning it is intensely responsive to external forcing with concomitant exacerbation of e.g., extreme events among other impacts Giorgi (2006). At the same time, the computational and time requirements for these high-resolution simulations are essential in assessing their added value.

The accuracy of dynamically downscaled simulations depend on several factors as the geographical ones in terms of the coastline or orography representation (Molina et al. 2022), the boundary forcing (Jury et al. 2015), the quality and uncertainty of observations (temporal and spatial), interactions between remaining parametrizations (Torma et al. 2015; Prein et al. 2015), or the temporal scale (Kotlarski et al. 2014). Previous research has shown that spatial

averaging of large regions, and/or averaging at the seasonal scale, tends to smooth the potential advantages associated with higher resolution modelling (Kotlarski et al. 2014). While the primary focus lies in accurately capturing convective processes, CPRCMs have demonstrated additional benefits or what is commonly referred to as “added value”. This includes improved seasonal forecasts (Schwitalla et al. 2020), a better representation of interactions with complex topography, urban influences, and land-sea contrasts (Argüeso et al. 2014). Added value of mean and heavy precipitation on seasonal or smaller temporal scales by the kilometer-scale simulations has been studied in multiple works (Adinolfi et al. 2020; Kendon et al. 2012; Chan et al. 2013; Prein et al. 2015, 2016; Fosser et al. 2015; Berthou et al. 2020; Fumière et al. 2020; Coppola et al. 2020; Ban et al. 2021), finding improvements in precipitation daily cycle, intensity and frequency representation. Although some shortcomings in representing maximum and minimum temperature at km-scale resolution have been seen in Soares et al. (2022), a more recent study (Sangelantoni et al. 2022) shows how CPRCMs simulations, although with a warmer/drier tendency, can reproduce heatwaves more realistically than their driving RCMs. Future scenario studies are still scarce, however, added value has been found in the projected patterns of change, in reference to the coarser resolution simulations (Pichelli et al. 2021). It has also been seen that in the CPRCMs projections, the sign of the precipitation intensity change in some regions is modified (Adinolfi et al. 2020), as well as the intensity and duration of the summer rain with respect to what was previously seen (Kendon et al. 2017).

Fewer studies have focused on the added value of wind representation by CPRCMs. The spatial and temporal variability of the surface wind is largely related to the fine-scale representation of the orography and land use in the climate models. (Wang et al. 2013; Cholette et al. 2015; Hackenbruch et al. 2016) show that wind channelling over a region in UK, Canada and Germany, respectively, is better represented by high resolution RCMs between 0.5 and 3 km resolution. In a study of local winds over the Adriatic region Belušić et al. (2018), the authors report that refining the grid spacing to a few km is needed to capture the small-scale low wind systems. Finally, the added value of CPRCMs in the wind field is found over the complex coastal terrain of the Adriatic region (Belušić Vozila et al. 2023), and in the modelling of very fine local mesoscale climate patterns over the UK (Wang et al. 2013).

The objective of this study is to analyse the added value presented in wind speed representation by the FPS-convection CPRCM and RCM hindcast simulations over the extended Alpine domain. The method applied to characterize the added value is the distribution added value (DAV) proposed by Soares and Cardoso (2018), already used for

wind speed evaluation of the EURO-CORDEX simulations in Molina et al. (2022), and for temperature and precipitation in Careto et al. (2021, 2022). The DAV metric allows the evaluation of the full probability density functions (PDFs) from seasonal to annual time scales, for the entire domain. In addition, for the extreme wind values, the maximum wind speeds above the 95<sup>th</sup> percentile of the PDFs are evaluated with the DAV metric. Furthermore, elevation and coastal-inland composites are examined to analyse the effects of improved orography and coastal features representation by the CPRCMs.

The document is structured as follows: Sect. 2 describes the observational and model datasets and the methodology used. The results are presented in section 3. Section 4 discusses the results and relates them to other findings in the literature. Finally, the main conclusions from this work are presented.

## 2 Data and methods

### 2.1 FPSCONV simulations

The CORDEX FPS convection-permitting hindcast simulations (Coppola et al. 2020) are available for the 2000 to 2009 period. The RCMs listed in Table 1 are the dynamical downscaled ERA-interim (ERA) reanalysis using two nested domains. The first domain encompasses the entire standard EURO-CORDEX Jacob et al. (2020) region with a resolution of 12–25 km, referred to as the pan-European domain (EUR domain). Then, a nested smaller domain covering the Alps area, known as the ALP domain (Fig. 1), is used as the corresponding convection-permitting configuration (CPRCMs) from each of those RCMs at 2–3 km. A Figure showing the wind speed representation over the ALP domain by the IDL-WRF model at the three different resolutions employed can be seen in the Supplementary material. It should be noted that the Met Office Hadley Centre (MOHC) simulations are an exception, since a direct downscaling from ERA-Interim to the 2.2-km grid was performed. For detailed information on the model configurations, please refer to the references given in Table 1.

### 2.2 Observations

The assessment of CPRCMs added value is focused on both the full PDF and its extreme sections. Thus, local station observations are used to avoid the smoothing effects caused by gridded datasets, which affect the PDF tails (Boberg et al. 2009). The observations are taken from the Met Office Hadley Centre's Integrated Surface Database (HadISD). HadISD, version 3.1.0.2019f (Smith et al. 2011; Dunn et al. 2012, 2016, 2019), is a global sub-daily dataset

based on NOAA's NCDC ISD dataset and distributed by the UK Met Office Hadley Centre (<https://www.metoffice.gov.uk/hadobs/hadisd/>). The representation of convective processes by CPRCMs can improve the representation of daily wind speed cycles by models. In that sense, hourly data should be used. However, due to the scarcity of hourly wind speed observations available to represent the whole territory, daily data were used. Stations with at least 90% of the time steps of the period 1996–2009 at the daily level (averaged from hourly data) within the common extended ALP domain, as in (Molina et al. 2021), were selected. Finally, 267 daily averaged wind speed series at 10 m height are obtained for the assessment (see Fig. 1 for more details on the meteorological stations).

### 2.3 Distribution added values (DAV)

The added value of using higher versus lower resolution simulations compared to observations is assessed by the DAV metric (Soares and Cardoso 2018). This method is based on the PDF skill score proposed by (Perkins et al. 2007) to evaluate the similarity between two PDFs. Here, the PDFs are calculated by binning the daily model data on native grids into bins of 0.5 m/s according to (Molina et al. 2021), and because it is the range in which the database of observations rounds in its control process Dunn et al. (2019). Then the data is normalised by dividing each bin value by the sum of the occurrences from all bins. Using the normalized PDF allows differences between seasons and regions to be compared, and changes in distributions to be accurately assessed Gutowski et al. (2020).

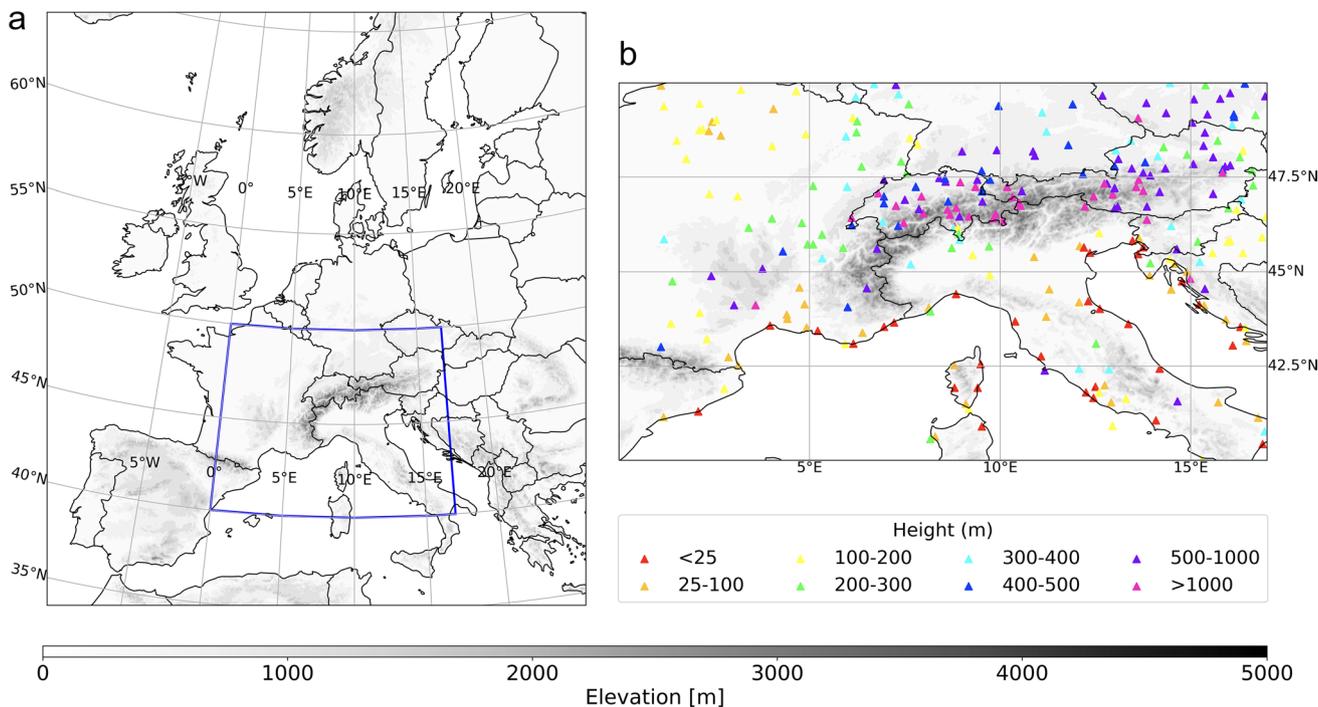
The added value is assessed by comparing each CPRCM with its driving RCM and ERA-Interim (the reanalysis that drives the RCM hindcast simulations), using observed wind speed observations data as the basis. Model data from the nearest grid point of each RCM and ERA-Interim relative to each wind station are used. If more than one station falls within the same model grid cell, all observations are combined to create the PDF. The possible impact of merging together wind regimes with different behaviour is analysed through a comparison of inland/coastal stations and stations at different altitudes. The time steps with missing values in the observation dataset are also removed from all models. In this way, the same number of valid time steps is used to create the PDFs in the added value calculation. Thus, the wind speed PDF for each observation station and corresponding model cell is computed, either the high or low-resolution model or the ERA-Interim data. A score (S) between 0 and 1 is then determined as a measure of the common area between the two frequency distributions:

**Table 1** Overview of Regional and Convection Permitting Climate Models used in the present study

Acronym	Institute	Reference	RCM ID	Resolution EUR domain	Resolution ALP domain
<b>AUTH</b>	Aristotle University of Thessaloniki	Skamarock (2008)			
	Department of Meteorology & Climatology Greece	Skamarock and Klemp (2008)	WRF381BG	15 km	3 km
<b>BCCR1</b>	NORCE & Bjerknes Centre for Climate Research Norway	Skamarock (2008) Skamarock and Klemp (2008)	WRF381BF	15 km	3 km
<b>BCCR2</b>	NORCE & Bjerknes Centre for Climate Research Norway	Skamarock (2008) Skamarock and Klemp (2008)	WRF381BA	15 km	3 km
<b>BTU</b>	Chair of Atmospheric Processes Brandenburg University of Technol- ogy (BTU) Germany	Keuler et al. (2016)	CCLM5-0-9	12 km	3 km
<b>CICERO</b>	Center for International Climate Research Norway	Skamarock (2008) Skamarock and Klemp (2008)	WRF381BJ	15 km	3 km
<b>CMCC</b>	Euro-Mediterranean Center on Climate Change (CMCC Foundation)	Adinolfi et al. (2020)	CCLM5-0-9	12 km	3 km
<b>CNRM</b>	Centre National de Recherches Météorologiques Météo-France, CNRS, France	Nabat et al. (2020) Caillaud et al. (2021)	CNRM-ALADIN & CNRM-AROME41t1	12 km (MED-CORDEX)	2.5 km
<b>ETHZ</b>	ETH Zurich, Institute for Atmospheric and Climate Science, Switzerland	Fuhrer et al. (2018) Leutwyler et al. (2017)	COSMO-crCLIM_5	12 km	2.2 km
<b>HCLIM</b>	(DMI, MET-NORWAY, SMHI) HARMONIE Climate Community	Belušić et al. (2020)	HCLIM38-ALADIN & HCLIM38-AROME	12 km (Extended ALP)	3 km
<b>ICTP</b>	Abdus Salam Internatinal Centre for Theoretical Physics, Italy	Giorgi et al. (2012) Coppola et al. (2020)	RegCM4-7	12 km	3 km
<b>IDL</b>	Instituto Dom Luiz, Faculdade de Ciências Universidade de Lisboa, Portugal	Skamarock (2008) Skamarock and Klemp (2008)	WRF381BH	15 km	3 km
<b>IPSL</b>	Institut Pierre Simon Laplace,LATMOS CIMA, CNRS, France	Skamarock (2008) Skamarock and Klemp (2008)	WRF381BE	15 km	3 km
<b>KIT</b>	Institute of Meteorology and Climate Research Germany	Doms and Baldauf (2011)	CCLM5-0-14	25 km (MiKlip)	3 km
<b>KNMI</b>	KNMI, Royal Netherlands Meteorological Institute, Nederland	Belušić et al. (2020)	RACMO & HCLIM38-AROME	12 km (Extended ALP)	2.5 km
<b>UCAN</b>	Universidad de Cantabria, Santander Meteorology Group, Spain	Skamarock (2008) Skamarock and Klemp (2008)	WRF381BI	15 km	3 km
<b>UHOH</b>	Institute of Physics and Meteorology University of Hohenheim, Germany	Skamarock (2008) Skamarock and Klemp (2008)	WRF381BD	15 km	3 km
<b>WEGC</b>	Wegener Center for Climate and Global Change, University of Graz, Austria	Skamarock (2008) Skamarock and Klemp (2008)	WRF381BL	0.1375°	0.0275°
<b>MOHC</b>	Met Office Hadley Centre United Kingdom	Berthou et al. (2020)	HadREM3-RA-UM10.1 -		2.2 km

**Table 1** (continued)

Acronym	Institute	Reference	RCM ID	Resolution EUR domain	Resolution ALP domain
FZJ	Institute of Bio- and Geosciences (Agrosphere, IBG-3) Research Centre Juelich, Germany	Skamarock (2008)	WRF381BB	15 km	3 km



**Fig. 1** **a** EURO-CORDEX full domain, with the common domain across all datasets delimited in blue. **b** Topography over the common ALP domain, where all computations were carried out. Points refer to

the HadISD wind speed observation stations analysed. Colours make reference to the altitude of the stations

$$S = \sum_1^n \min(Z_m, Z_o) \tag{1}$$

where  $n$  is the number of bins used to calculate the frequency distribution for a given location,  $Z_m$  is the proportion of values in a given bin of the model, and  $Z_o$  is the proportion of values in a given bin of the observed data. The sum of all  $Z_m$  or  $Z_o$  is 1. If the overlap between the frequency distribution of wind speed for the observations and the modelled data is complete, the score is 1; otherwise, the score will be between 0 and 1. Regarding this comparison method, it should be noted that the frequency distribution of the observations refers to a specific location, whereas the frequency distribution of the models represents an entire grid area. Furthermore, the contribution of the individual bins to the overall score decreases as one approaches the tails. This is a

consequence of normalisation, which can lead to an under-representation of the extremes.

Finally, the daily mean wind speed DAV for the entire PDF is determined using the relative difference between the high (hr) and low (lr) resolution model scores for a given season or region:

$$DAV = 100 * \frac{S_{hr} - S_{lr}}{S_{lr}} \tag{2}$$

where  $S_{hr}$  and  $S_{lr}$  are the scores for the high (CPRCMs) and low-resolution (RCMs) models, respectively. High resolution has added value if the joint overlap between the model and the observed PDFs is greater than the overlap at low resolution. Ultimately, the DAV represent the percentage of added (positive) or lost (negative) value associated with the higher resolution relative to the lower resolution, with values

ranging from  $-100$  to  $+\infty$ . To evaluate DAV concerning extreme wind speeds, we also calculate the added value for the PDF section above the 95<sup>th</sup> percentile of observations ( $DAV_{p95\_p100}$ ), following (Soares and Cardoso 2018; Cardoso and Soares 2022). First, the part of the PDF above the 95th percentile threshold of observations is extracted, and then the DAVs are calculated such that the sum of  $Z_m$  and  $Z_o$  is also 1 for the partial PDFs. Although the choice of percentiles is somewhat arbitrary, the 95<sup>th</sup> percentile was chosen following previous studies (Frank et al. 2020; Outten and Sobolowski 2021).

DAV results are shown for the EUR vs ERA, ALP vs ERA and ALP vs EUR to assess the added value of the RCMs and CPRCMs against the forcing ERA, and the added value of CPRCMs in comparison with the RCMs, respectively. First, DAV is calculated by pooling together all data from the nearest grid points of each CPRCM (ALP), RCM (EUR) and ERA-Interim to the observed station data for the whole area. Second, a spatial approach is adopted by grouping only the information within each individual cell of the reanalysis or RCM, independently for each resolution of the simulations. To investigate the added value of models in representing the wind at coastal regions, stations located within the model grid cells located along the coast or further inland are selected. According to Molina et al. (2022), grid cells are defined as coastal or inland based on their proximity to the coast, with coastal grids being those where stations are located within a distance of less than 0.1 degrees (approximately 10 kms) from the coastline. The added value linked to orography is assessed by creating elevation composites, attempting to obtain a similar number of stations for each elevation bin, and then selecting the appropriate grid cell. The PDFs for each composite are created considering only the grid points under the specific condition, considering the model grid boxes as the nearest neighbours of the local observation stations. Then, the DAV for each composite is calculated and compared to investigate their differences.

### 3 Results

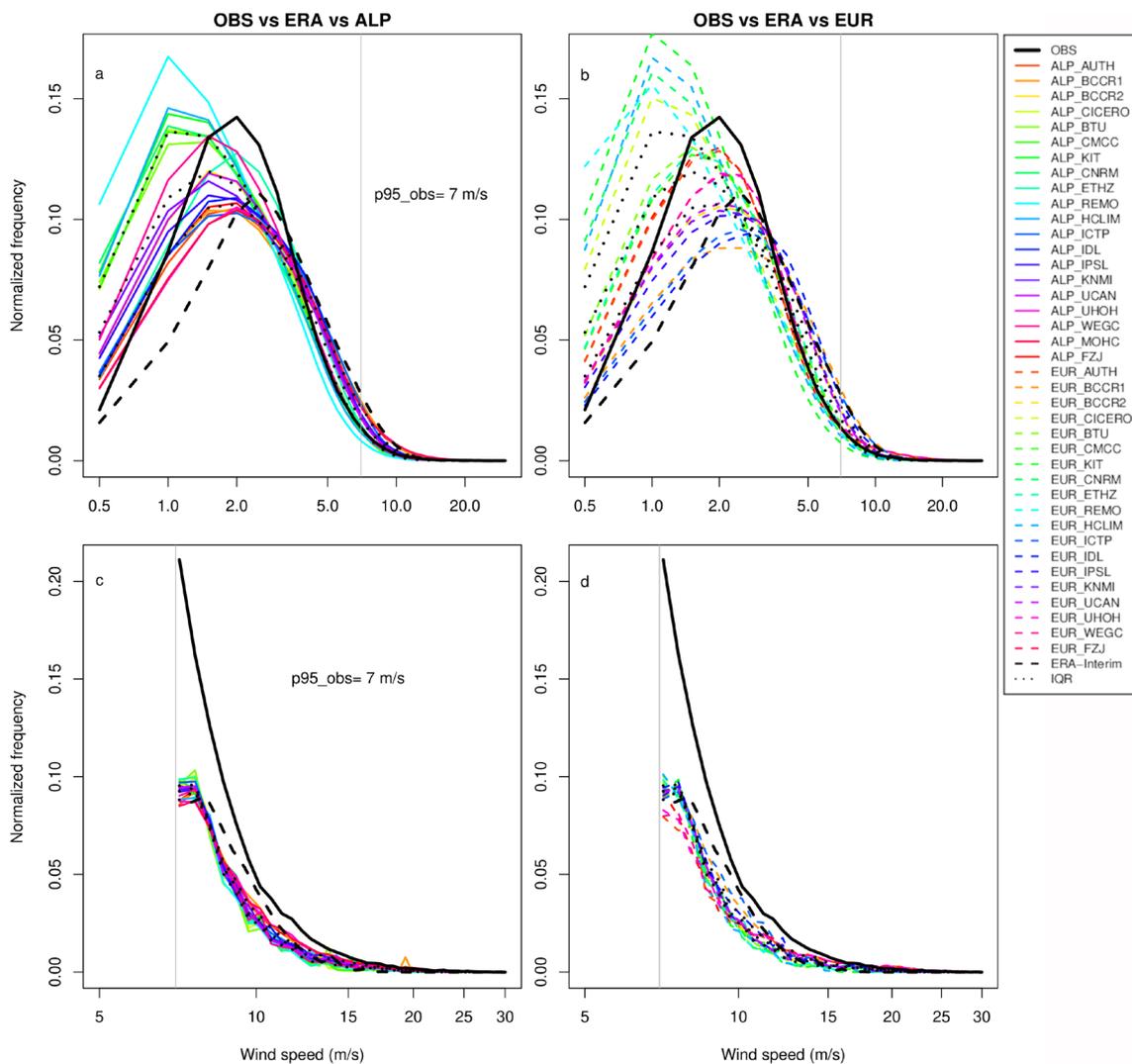
#### 3.1 Annual and seasonal analysis

The regional PDF (for grid points where there are observations) of the daily mean wind speeds for all datasets considered is shown in Fig. 2a and 2b to study its degree of agreement, and the seasonal PDFs in Figure S2 of the Supplementary material. The highest frequencies occur at wind speeds between 2–4 m/s for the observational PDF, following a Weibull distribution (Conradsen et al. 1984). In general, the lowest frequencies of observed daily winds (low and high winds) are underestimated by the RCM and CPRCM simulations, while the highest frequencies (mean winds) are

overestimated, as previously seen in Molina et al. (2022) for the EURO-CORDEX runs. Although there is a big spread among RCMs (dashed lines at the top right of Fig. 2), the CNRM, HCLIM, ETHZ, BTU and ICTP EUR resolution simulations tend to overestimate the wind speed frequencies below 2 m/s, which could have a significant impact on the DAV obtained. The opposite occurs with the BCCR1, IDL and IPSL RCMs, which greatly underestimate the wind speed frequencies below 4 m/s.

Figure 3 displays the DAV values (in percentage) for the daily wind speed PDFs for the full year and for each season of the CPRCM and RCM simulations compared to its forcing (ERA-Interim) or the CPRCM to its coarser resolution RCM (ALP vs EUR). The larger the DAV value, the greater the added value of the higher-resolution model in representing the observational PDF. In Fig. 3a, RCMs reveal negative DAV values compared to the ERA-Interim reanalysis, lower in winter than summer, indicating the worst representation of the observed wind speed by the simulations with a 12–25 km resolution over the Alpine area. At the yearly scale, negative DAVs prevail in 10 of the 18 RCMs, with annual values between 0 and -8%, and positive in the other 8 models, with DAV values between +2 and +9%. Added value is obtained in the comparison between the CPRCM simulations and ERA-Interim (Fig. 3b), with lower (more negative) values in winter (DJF) relative to summer (JJA). HCLIM (from  $-2$  to  $-17\%$ ) presents the worst DAV value and REMO (from +2 to +8%) and UHOH (from +0.5 to +6%) the best DAV results, in all seasons except JJA. In summer, MOHC has the largest and WEGC has the lowest DAV. In the comparison of the ALP with the EUR simulations (Fig. 3c), an added value in the wind speed representation is seen in the CPRCMs, with annual DAV values between +2 and +10% in 11 out of 18 simulations. Although it depends on the model, this improvement is usually larger in summer than in winter. The opposite (larger DAV in winter than summer) is found in those simulations with negative DAV values for the RCMs, such as AUTH and BCCR1. These results are consistent with the previous comparisons (detrimental effect of EUR and added value of ALP vs ERA), since in most cases, the ALP partly corrects the negative values of the EUR resolution.

The added value has also been computed for the grid points of the models and reanalysis, to obtain the DAVs spatial distribution. In the comparison between EUR and ERA (top of Fig. 4), the simulations agree on the added value for most of the inland areas, while a loss of value for the Alps, the Italian peninsula and Corsica is shown (with mean DAV around  $-30\%$ ). In the ALP compared to ERA (centre panel of Fig. 4), the models with positive DAV are concentrated mostly over the Alps while negatives are widely distributed over the domain, with the lowest DAV over the Mediterranean coast of Italy in summer.



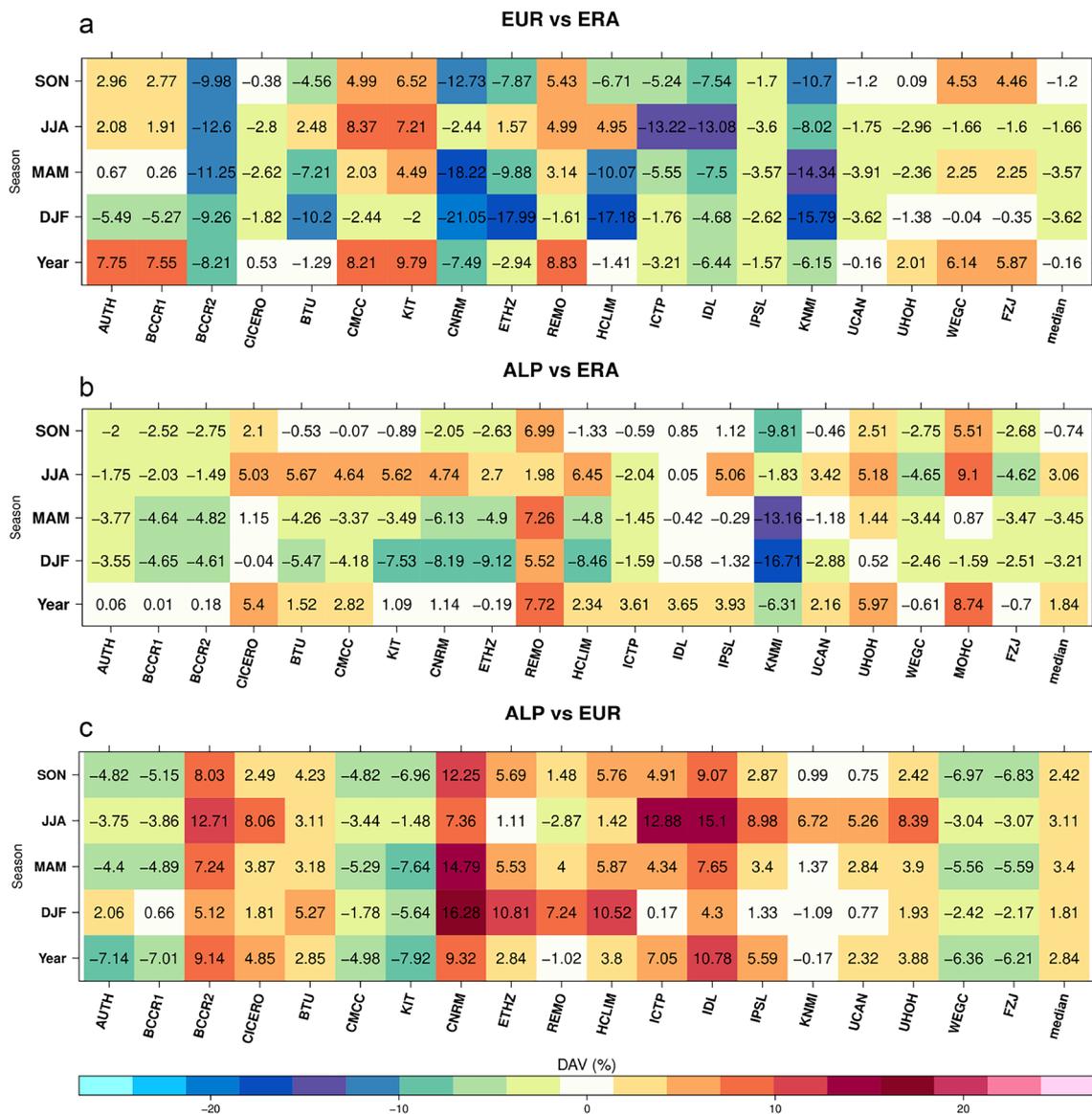
**Fig. 2** Yearly wind speed distributions (**a**, **b**) and distributions above the 95th percentile of observations (**c**, **d**) taken from the daily hind-cast simulations of the FPS-CONV project, the ERA-Interim reanalysis (2000–2009) and the observational data used to build the DAV. The **a** and **c** panels show the distributions for the ALP domain, and

the **b** and **d** panels for the EUR domain simulations. The dotted lines represent the interquartile range (IQR), the upper and lower line being the 75th and 25th percentiles of the models, and the intermediate line being the median

In concordance with Fig. 3 for the full domain, an added value between 0 and +10% is obtained in the comparison of ALP and EUR (bottom of Fig. 4). However, there are some spatial details that are smoothed in the analysis for the full domain. In this sense, there is a model agreement in the added value over the Swiss Alps and the Mediterranean coast, reaching mean DAV values up to +40%. In general, it is difficult to provide a spatial picture due to the high variability among models, since there are adjacent cells with different results and even cells with positive and negative results for different models. Nevertheless, inter-seasonal differences can be seen, with larger DAV over the coast in summer than in winter.

### 3.2 Annual and seasonal analysis: upper-tail PDF

As in the previous section, the PDF of the wind speeds above the 95<sup>th</sup> percentile of the observations (7 m/s) as represented by observations, ALP and EUR simulations and ERA-Interim, are displayed in Fig. 2 (bottom). It is seen that the frequency of observations is much larger than the others, probably because observations represent one point whereas gridded data represent the averaged grid values, producing a smoothing effect in extremes Boberg et al. (2009). Figure 5 shows the DAV values for the wind speed section of the PDF regarding the wind speed bins above the 95<sup>th</sup> percentile of the observations. Overall, the models reveal larger



**Fig. 3** Regional annual and seasonal distribution added value (DAV, in percentage) of the daily wind speed considering the whole PDF taken from the hindcast CORDEX FPS-Convection simulations. EUR vs ERA (a) represents the DAV between the RCM simula-

tions against the ERA-Interim reanalysis, ALP vs ERA (b) the DAV between the CPRCM simulations against the ERA-Interim reanalysis and ALP vs EUR (c) measures the DAV between the CPRCM and the RCM simulations

DAV values for extreme winds than for the full PDF, given by the CPRCM and RCM simulations against the driving ERA-Interim. Among seasons, the DAV is generally larger in summer in comparison to winter in the three analyses, which is owed to the better performance in representing the observed wind extreme PDFs for winter by the models with a larger resolution, as shown in Figure S3. Figure 5 shows four RCM chains (AUTH, BCCR, ICTP and WEGC), where the RCM (Fig. 5a) performs badly (with DAV from  $-5$  to  $-19\%$ ) and CPRCM (Fig. 5b) improves the DAV strongly (in the range of  $+3$ – $9\%$ ), which is then reflected in the large DAV for the ALP vs EUR comparison (Fig. 5c). These WRF

runs employed the YSU boundary layer scheme (a simple k-profile parameterization), whereas the others employed the MYNN2 scheme (a more sophisticated turbulent kinetic energy parameterization). These results seem to indicate that the YSU scheme might be less well suited to convection permitting scales. Previous evaluations of the added value of increasing resolution in the EURO-CORDEX RCMs for temperature and wind variables Careto et al. (2022); Molina et al. (2022) show that DAV values cluster around the GCMs rather than the RCMs. That is, the values are similar for models driven with the same GCM, in contrast to the values found in RCM forced by different GCMs. Here, it is seen

that the chain of ALP simulations forced by the CCLM RCM (BTU, CMCC and KIT) show a behaviour that could be dependent on the RCM, as DAV values are positive in the EUR vs ERA and negative in the ALP vs ERA comparison. Some models present positive values in all seasons. In the EUR vs ERA comparison (Fig. 5a), 7 out of 18 simulations obtain DAV values in the range of +3–9%, while 12 out of 18 models obtain DAV from +0.3 to +11% in the ALP vs ERA analysis (Fig. 5b). In general, the CPRCMs (ALP) seem to show a neutral effect (from +5 to –3%) compared to the RCM (EUR), except for the four chains of models mentioned before. The results reflect that those models with greater deficiencies in the EUR vs ERA comparison better represent the high extreme winds at higher resolution, with DAV values around +4–26% depending on the model and season.

As for the full PDF, the spatial distribution of the DAV for the upper-tail PDF is shown in Fig. 6. In general, it is seen that the ALP adds value to the EUR resolution in the description of the strongest winds. The EUR vs ERA comparison displays positive DAV inland, especially in summer, and negative DAV over the mountains and the coast of France. The spatial picture shows that the previously mentioned negative DAV values for AUTH and BCCR2 in the EUR vs ERA analysis are distributed across the Alps (see Supplementary material). For WEGC, however, the negative DAV values are distributed over the whole domain. In comparison to ERA, ALP simulations present added value widely distributed, with mean positive DAV between +5–25%, and detrimental effects over the Italian peninsula in summer. Compared with the entire domain view (Fig. 5), where most models display a small detrimental effect and some models a large added value, the DAVs spatialization shows that there are more models producing a positive added value in the evaluation of the higher-resolution simulations against the coarser (bottom panel of Fig. 6), with mean DAV values from +5 to +35%. Negative DAV can be seen for some models over Switzerland, the Alps and the Italian peninsula, with mean DAV between 0 and –15%, except for some points (in blue colour) that reach up to –40%.

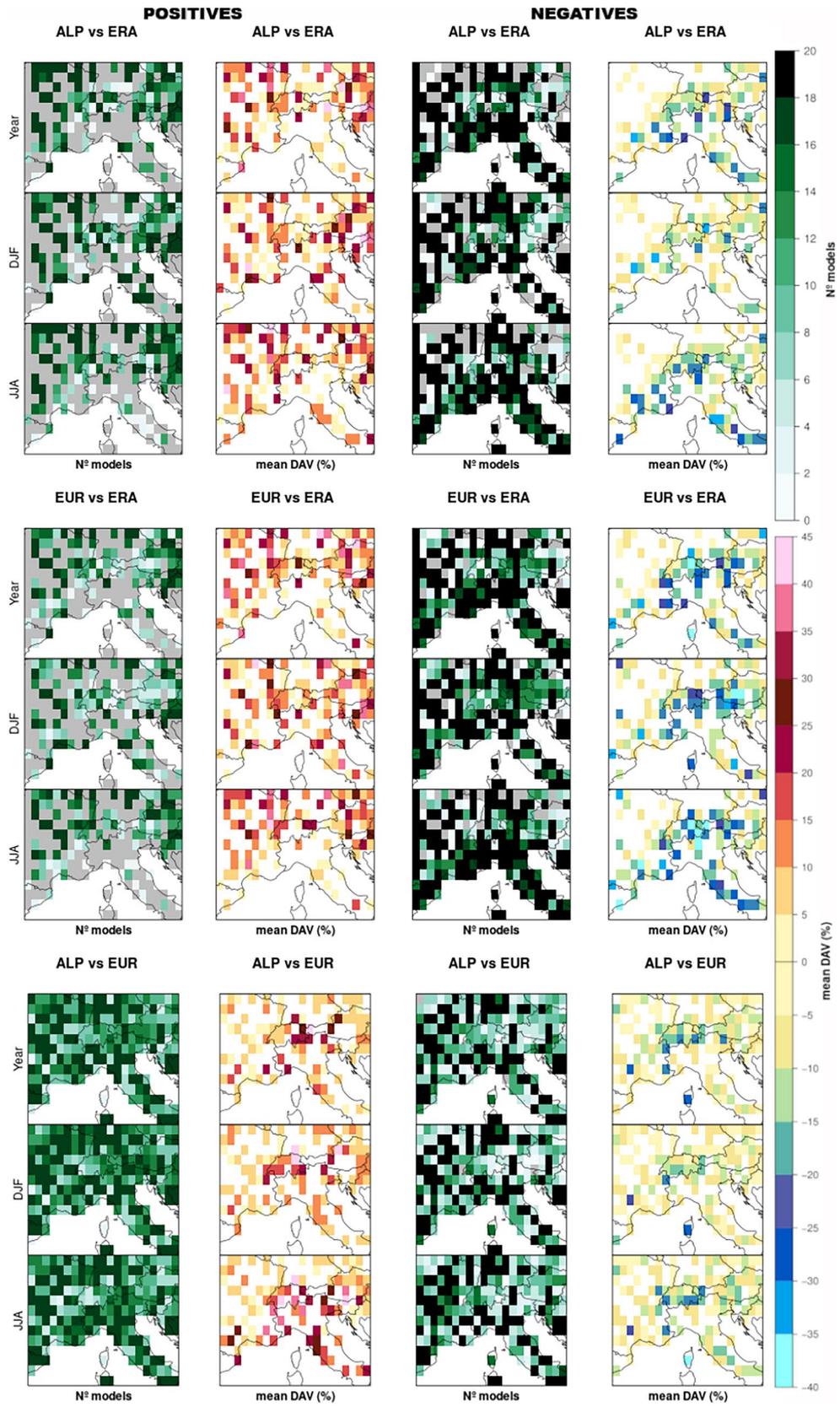
### 3.3 Orography dependency

The Alps region exhibits complex orographic characteristics, where the model resolution should play a crucial role in accurately representing wind patterns and, subsequently, CPRCMs should give an added value. The orography dependent added value is examined by selecting observation stations in altitude bins and then by computing the DAV of the corresponding model grid cells. In Fig. 7, both CPRCMs and RCMs demonstrate a better wind speed representation than ERA-Interim with increasing altitude from 100 m up to 400 m. Below 100 m, the DAV increases with altitude but remains negative. Above 400 m, the DAV decrease with

altitude, more pronounced in the EUR simulations (with negative values) than in the ALP domain simulations (with positive values). The lowest DAV for the annual PDF are found at altitudes below 25 m (with median values close to –10%, reaching –20% for winter PDF), indicating that ERA-Interim better represents the observed PDF at this altitude compared to the simulations, while the highest DAV occurs at 300–400 m (with median values around +15%). Seasonally, it is seen that the ALP simulations show positive DAV values with respect to ERA-Interim in all height composites in summer, indicating an improvement of the wind representation during this season due to higher spatial resolution. When comparing ALP with EUR (bottom panel of Fig. 7), median values show an added value in the wind speed representation at all altitude bins studied, all seasons. DAV are positive for the range of altitudes below 100 m and between 300–500 m in the annual PDF, and they are negative in the others. In contrast to previous comparisons, added value is also observed at stations above 1000 m in the most extreme seasons, summer and winter, meaning that the orography is more realistically represented by the convection-permitting models. It must be taken into account that, due to the limited number of observation stations available above 1000 m, the assessment of the added value in the most complex topography regions could be limited. However, the absence of observations does not imply an absence of added value. Although DAV values are not very high, from these results it can be concluded that CPRCMs provide added value in representing wind characteristics with no significant differences among seasons, particularly at low and medium altitudes, while performance is relatively poorer at very high stations, except for summer and winter.

### 3.4 Coast-inland analysis

The coastal circulations are driven by the interconnection of marine and terrestrial atmospheric boundary layers, the air-sea interaction, the large-scale dynamics and the coastal ocean circulation Rogers (1995) and, therefore, are very dependent on specific local morphological features. These are often poorly represented by models (Outten and Sobolowski 2021). The wind representation in these areas is analysed here by computing the DAV in the coastal and inland grid cells separately. Results present negative DAV values for the coastal stations and positive for the inland regions (Fig. 8) in comparison with the forcing reanalysis, indicating that coastal wind PDFs seem to be better described by ERA-Interim than with any of the RCMs or CPRCMs when compared with available observations. ERA-Interim assimilates directly observational information along the coast until 2007 (Dee et al. 2011), therefore, even though the high-resolution models are better able to represent sea breezes and other land-ocean interactions, they will have



**Fig. 4** Annual, winter (DJF) and summer (JJA) distribution added value (DAV) of the daily wind speed for the CORDEX FPS-Convection simulations. The first (third) column represents for each cell the number of models (out of 18) that obtain positive (negative) DAV. The second (last) column shows the mean DAV value for the simulations with positive (negative) DAV results. ALP vs ERA measures the DAV between the CPRCM simulations against the ERA-Interim reanalysis, EUR vs ERA measures the DAV between the RCM simulations against the ERA-Interim reanalysis and ALP vs EUR measures the DAV between the CPRCM and the RCM simulations

difficulties in presenting added value. In spite of this, a slight improvement is seen in the ALP comparison with the EUR resolution (third column of Fig. 8) regardless of the season of the year, with positive median DAV both along the coast (+1% for the annual PDF) and inland (+2.5%) regions. Seasonally, larger DAV values are obtained in summer compared to winter. This is particularly noticeable along the coast when comparing EUR to ERA (first column of Fig. 8), and inland when comparing ALP to ERA (second column of Fig. 8). Additionally, when comparing ALP to EUR, the spread among models is larger in both winter (DJF) and summer (JJA) than during the intermediate seasons.

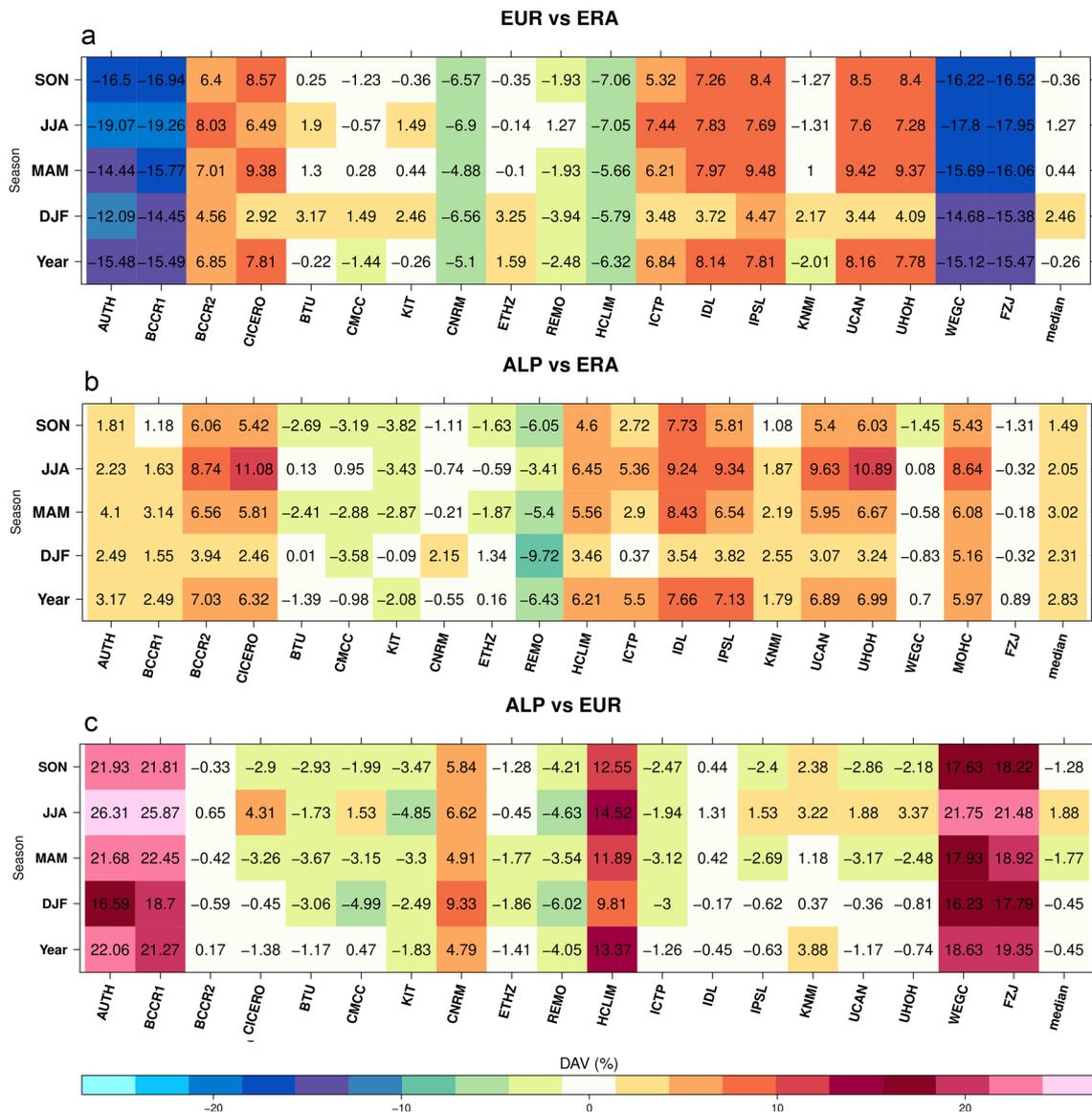
## 4 Discussion and conclusions

Several studies have explored the behaviour of the high-resolution models at convection-permitting scale (or km-scale) in recent years, focusing mainly on the representation of precipitation and temperature (Adinolfi et al. 2020; Ban et al. 2021; Coppola et al. 2020; Kendon et al. 2012, 2017; Pichelli et al. 2021; Prein et al. 2013; Sangelantoni et al. 2022). The present study investigates the added value for describing the surface daily wind speed of the latest generation of very high-resolution climate models at convection-permitting scale (CPRCMs). The hindcast experiment (2000–2009 period) of the whole multimodel ensemble from the CORDEX-FPS Convection initiative is analysed for the first time over an extended Alpine domain for the wind field. Since hindcast simulations are forced at their lateral boundaries by ERA-Interim reanalysis (considered the perfect framework), an added value may be expected in the representation of regional to local atmospheric features (Prein et al. 2015). The model performance with respect to coarser resolution counter-parts is inspected through the distribution added value (DAV) metric (Soares and Cardoso 2018); in which the normalised wind speed probability density functions (PDFs) from the CPRCMs, their driving convection-parameterized RCMs and its forcing reanalysis (ERA-Interim) are compared with their corresponding observational PDF as a reference.

In general, results show that CPRCMs add value to their forcing RCM in the representation of the PDF of daily wind

speed, but the magnitude of the improvement and nature varies depending on the model, the region and the season. Results reveal added value in the CPRCMs comparison with ERA-Interim in summer and detrimental in winter, indicating the poor/good quality of the models of higher resolution in representing the observed wind speed PDFs of these seasons. This result is consistent with the previously seen for the EURO-CORDEX simulations in Molina et al. (2022) and for the simulations of marine near-surface wind fields in Sotillo et al. (2005); Kanamitsu and Kanamaru (2007); Winterfeldt and Weisse (2009); Winterfeldt et al. (2011). According to these previous studies, the reason behind this is the misrepresentation of local processes typical for summer in mountainous regions by ERA-Interim forcing, due to its coarser resolution. Furthermore, the strength of the large-scale atmospheric flow decreases in summer, giving more importance to the local phenomena best captured by the higher-resolution models. Previous studies have found improvements in the representation of daily summer precipitation or temperature with CPRCMs, either due to improvements in the simulation of convection or due to the representation of local phenomena associated with a better representation of orography-related processes (Prein et al. 2013). Consequently, an improvement in the representation of wind speed may be linked to air circulations forced by such orographic characteristics or by inhomogeneities that are better described by higher resolution RCMs, which could affect the movement of air masses. In addition, CPRCMs generally provide added value to their forcing RCM in most models and seasons. This is a relevant result for wind speed dynamical downscaling, since Belušić Vozila et al. (2023) did not find a clear added value in CPRCMs when considering the entire PDF in the Adriatic region.

The larger DAV values obtained for the upper tail of the observed PDF in the comparisons of EUR and ALP vs ERA indicate that extreme wind representation is more sensitive to changes in resolution than the mean wind speed. On the other hand, in the ALP vs EUR comparison, the results for the wind extremes seem to indicate that for the entire region, there are more models that show a neutral or even a slightly detrimental effect on the CPRCMs with respect to the RCMs. However, the regional PDF masks the spatial results, where there is large variability. It is observed that most of the models present positive DAV in all the grid points, albeit with a moderate level of added value, except for a few points. It is also seen that there are a few ALP models that perform worse than the EUR ones in terms of added value, but their detrimental is larger, resulting in low DAV values in the regional calculation. Therefore, it can be stated that most CPRCMs can more realistically simulate strong winds than the lower-resolution RCMs. This result would confirm the potential added value of CPRCMs anticipated by Belušić Vozila et al. (2023). Similar results



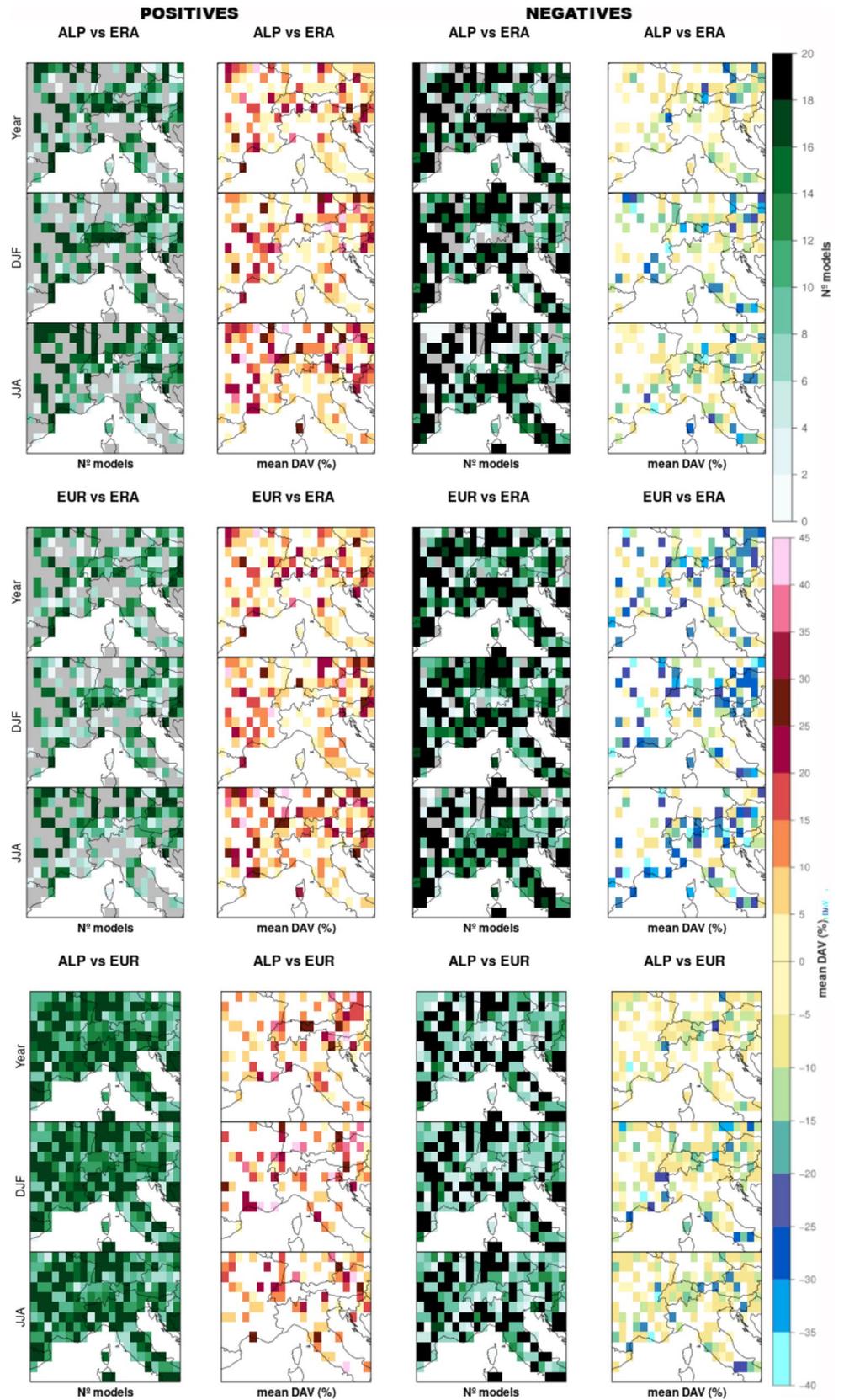
**Fig. 5** As Fig. 3, for the wind speed partial PDF regarding the wind speed bins above the 95<sup>th</sup> percentile of the observations

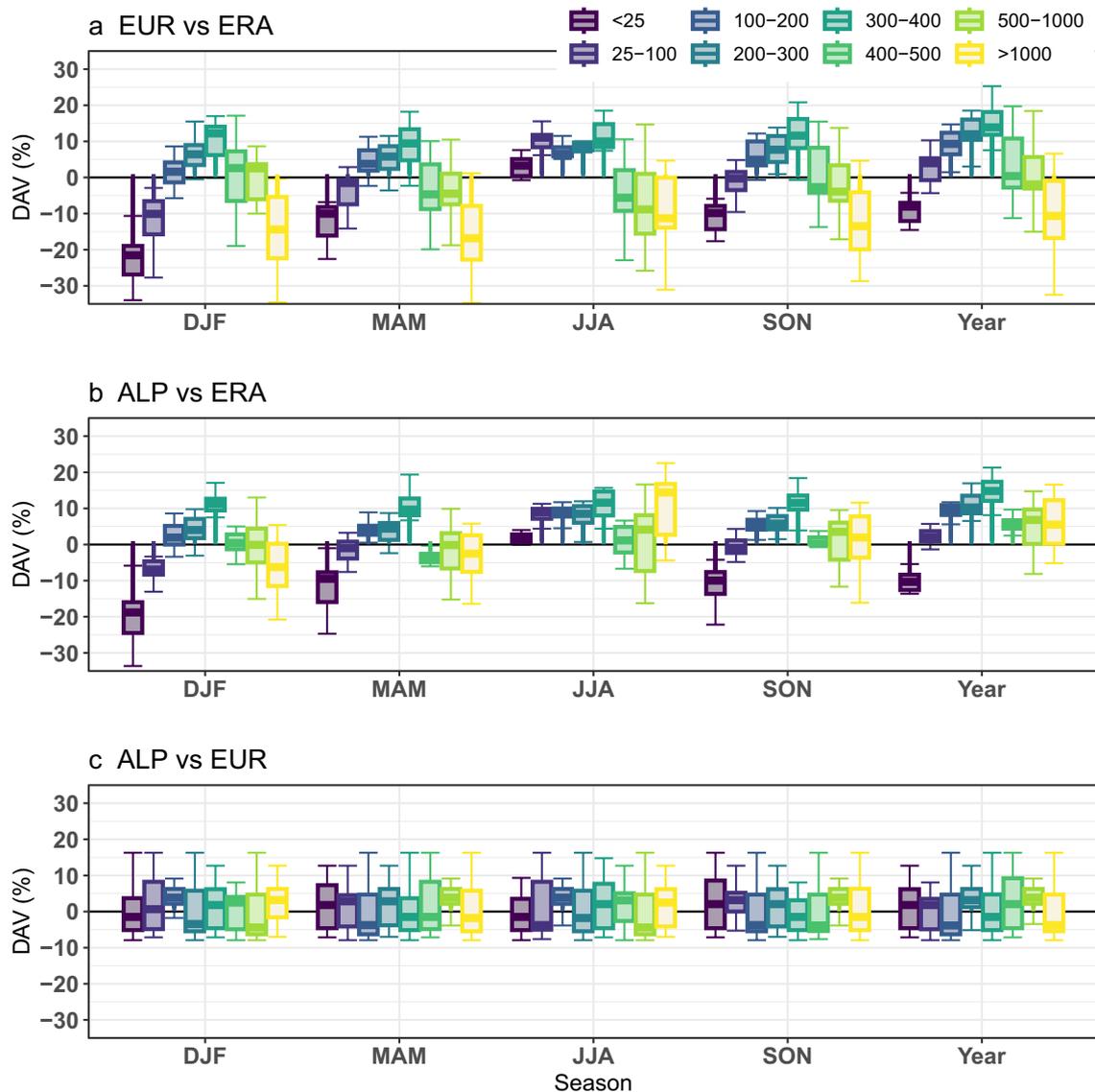
were also obtained for the daily maximum wind speed of the EURO-CORDEX models in Molina et al. (2022); Outten and Sobolowski (2021). The refinement in the description of small-scale processes is probably related to a better description of the friction generated by the terrain, the acceleration of the flow over the mountains, not resolved by the low-resolution models (Cardoso et al. 2016; Jiménez and Dudhia 2012; Nogueira et al. 2019; Outten and Sobolowski 2021), and the spatial variability of the gusts over complex terrain (Kunz et al. 2010). This improvement is slightly larger in summer than in winter, contrary to what was seen in Belušić Vozila et al. (2023) for the Bora wind events. Model dependency of the CPRCMs from the RCMs was seen in previous works for temperature (Soares et al. 2022)

and wind (Belušić Vozila et al. 2023) variables. Although it is not achieved in a general way in all the simulations, a certain dependency behaviour is seen in the models forced by the CCLM RCM (BTU, CMCC and KIT) in the results of the extreme winds, as DAV values for these models are positive in the EUR vs ERA comparison and negative in the ALP vs ERA comparison.

In regions with very complex topography or land-sea contrasts, local processes are generally difficult to capture with low-resolution models (Laprise 2008; Rummukainen 2010). Our results show that the CPRCMs better represent the wind at low and medium range of altitudes, where a more detailed depiction of terrain features such as valleys could play a relevant role. The negative DAV obtained in comparisons with

**Fig. 6** As Fig. 4, for the annual and seasonal distribution added value (DAV) of the daily wind speed for the CORDEX FPS-Convection simulations above the 95<sup>th</sup> percentile of the reference observations





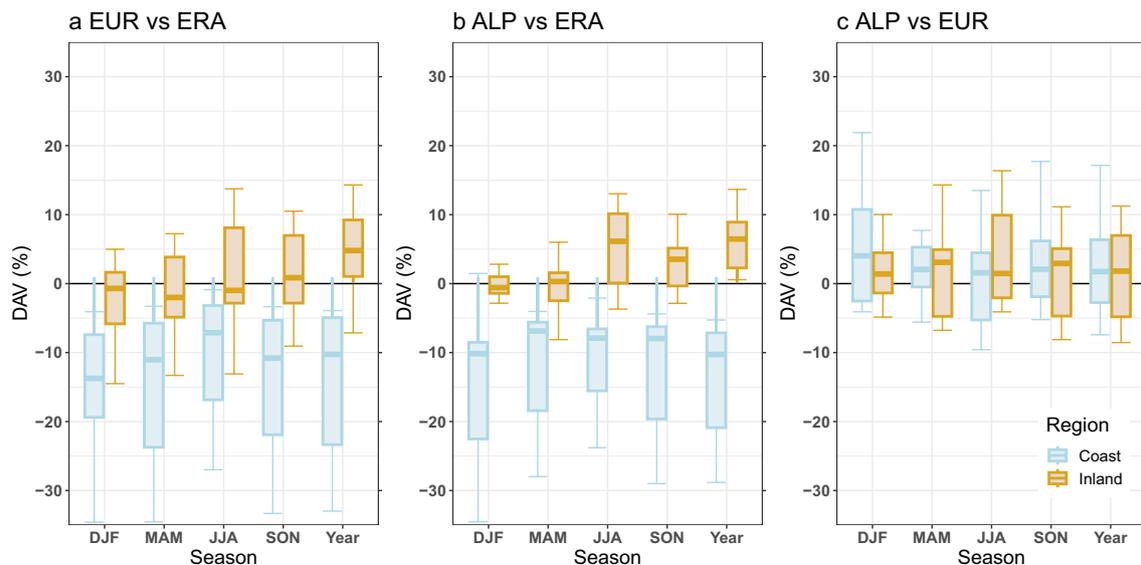
**Fig. 7** Composite of the DAV for the full annual and seasonal wind speed PDF. The first **a** and second **b** rows represent the ALP and EUR results, respectively, versus ERA-Interim, and the third row **c** is the comparison of the CPRCMs versus the RCMs (ALP vs EUR).

Each box represents the DAV of the wind speed observation stations below 25 m height, between 25 and 100 m, between 100 and 200 m, between 200 and 300 m, between 300 and 400 m, between 400 and 500 m, between 500 and 1000 m and higher than 1000 m

ERA at altitudes lower than 25 m are related to the assimilation of observations by ERA-Interim in coastal areas, where these stations are located. For the higher altitudes, the low DAV may be related to the growing influence of the free atmospheric flow, which is governed by large-scale forcing (De Wekker and Kossmann 2015). This large scale can be captured by reanalyses or even GCMs reasonably well, yielding very high skill scores. In that case, regional models reveal difficulties to add value, thus small deviations can actually have an important impact on the DAV. Besides, when compared with observation points in regions with complex orography, a certain degree of smoothing results

in the description of the real altitude, since the dynamic equations are discretized in grids of finite size (Niermann et al. 2019).

Previous works show the added value of dynamical downscaling by RCMs in the near-surface wind speed representation over the coast, where the land-sea contrast and associated local wind regimes become important (Sotillo et al. 2005; Kanamitsu and Kanamaru 2007; Winterfeldt and Weisse 2009; Winterfeldt et al. 2011). As for CPRCMs, Hernández et al. (2023) presents wind breezes better represented by CPRCM, and Belušić Vozila et al. (2023) determines their potential added value in representing



**Fig. 8** As Fig. 7, for the wind speed observation stations near the coast (blue boxes) and inland stations (brown boxes)

smaller-scale wind structures where wind speed and direction are more variable. Here, a detrimental effect is obtained compared to ERA-Interim. This is probably due to the fact that even though ERA-Interim does not represent the observed PDF perfectly, it assimilates observations on the coast and, therefore, it is more difficult for the models to add value. However, a slight added value of CPRCMs is seen in reference to the intermediate RCMs (EUR domain) both in the coast and inland regions. Gains over the Mediterranean coasts due to improved coastal dynamics from the increase in the resolution were observed for temperature in (Soares et al. 2022).

In this work, added value is found in the representation of observed wind speed by simulations at the convection scale over an extensive alpine area, most probably through better-resolved topography or through a better representation of ocean-land contrasts in the atmospheric flow. Higher spatial resolution and better representation of convection processes on those simulations would result in an improved representation of wind statistics compared with the standard 12 km RCM ones, or the forcing ERA-Interim reanalysis. Nevertheless, when examining seasons, elevation dependency, coastal regions, or the overall spatial distribution, the comparison yields mixed results. These findings present opportunities for further analysis. For instance, investigating the improved representation of local circulations caused by orography, particularly in the challenging Alpine region for wind description, or conducting a more detailed analysis over coastal areas can provide valuable information to clarify the results presented. Additionally, it would be of interest to study whether future projections of wind speeds based on km-scale simulations align with prior simulations conducted

at coarser scales, as GCMs and RCMs seem to project an opposite signal, and extreme events could increase under climate change conditions. Moreover, improving knowledge about the modelled description of wind features is relevant not only for model developers but also for impact studies.

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**Availability of data and materials:** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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