# Evaluation of the near-surface wind field over the Adriatic region: Local wind characteristics in the convection-permitting model ensemble

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## ABSTRACT

We present the first evaluation of the wind field from the CORDEX-FPS ensemble of kilometer-scale simulations, with focus on the Adriatic region. Kilometer-scale climate models, also known as convection-permitting models (CPMs), produce a good representation of small-scale topographic features and consequently a more detailed depiction of dynamical and thermal circulation. These enable a reliable view of climate characteristics of the wind field, especially in coastal regions and over complex terrain, such as the Adriatic. We investigate the (potential) added value introduced by CPMs compared to classical "cumulus-parametrized" regional climate models (RCMs), reanalysis and station observations. For this purpose, wind components at 10 meter level are used at 3-hourly frequency. All simulations cover a 10-year period, extending from 2000 to 2009. In terms of the standard statistical parameters such as correlation coefficient and temporal standard deviation, CPMs are very dependent on their parent RCM performance. However, the orographic forcing emphasizes the potential added value and CPMs contain some fine spatial scale variability (i.e. stronger extremes by 25% and accurate wind direction) that is absent in coarser RCMs and reanalysis. The potential added value is higher in the cold season compared to the warm season due to the proportion of severe wind events. CPMs reproduce well the typical wind regimes along the Adriatic coast, namely Bora and Sirocco. The benefit of using CPMs is especially pronounced in simulating Bora maximum wind speeds in northern Adriatic and Sirocco frequencies in southern Adriatic. Based on our overall analysis, we conclude that CPMs provide added value compared to coarser models, especially in the complex coastal terrain.

**Keywords**: Adriatic; Bora; Convection-permitting models; CORDEX; Regional climate models; Sirocco; wind

## 1. INTRODUCTION

Evaluation of the wind field over complex terrain provides an excellent opportunity to assess the reliability of the climate model simulations. However, it is a challenging task due to the limited accessibility of observational data and high variability in both speed and direction. Consequently, extensive studies comparing the modeled and observed climate characteristics of the wind field over particular parts of the Mediterranean region, where winds are strongly affected by topography (e.g. Ulbrich et al. 2012), are still rare (Obermann et al. 2016, Bonaldo et al. 2017, Belušić et al. 2018), especially on a sub-daily scale. However, sub-daily wind data is crucial in detecting the most severe wind events. Therefore, the evaluation of very high-resolution climate models, in coastal regions and over complex terrain such as the Adriatic, can reveal whether they achieve a good representation of small-scale topographic features and hence more details in dynamical aspects. Moreover, the evaluation of the wind for the present climate is needed for building confidence in wind field projections over future decades.

In the last decade, the international framework coordinating regional climate simulations with the highest available horizontal resolution was the Coordinated Regional climate Downscaling Experiment (CORDEX). EURO- (Jacob et al. 2020) and MED- (Somot et al. 2011, Ruti et al. 2016) CORDEX simulations at 0.11° (~ 12 km), which cover the Mediterranean region and the European continent, respectively, were used in a large extent to access climate variability and projections. Moreover, the CORDEX results showed added value and served as input for climate change impact and adaptation studies within the Fifth and Sixth Assessment Report (AR5 and AR6) of the Intergovernmental Panel on Climate Change (IPCC) and beyond (Patarčić et al. 2014, Gajić-Čapka et al. 2015, Belušić et al. 2018, Belušić Vozila et al. 2019). Referring to the Adriatic region, Belušić Vozila et al. (2019) have already analyzed the wind field projections using a multi-model ensemble composed of CORDEX regional climate models (RCMs) which showed a good performance when compared to the daily observed wind (Belušić et al. 2018). However, there is still space left for improvements, especially over the complex coastal region, where local winds often reach severe speeds due to the interaction with coastal topography.

Recently, an increasing number of studies show improvements in performances, when the grid spacing is further refined to 3-1 km (e.g. Ban et al. 2014, Ban et al. 2015, Meredith et al. 2020, Adinolfi et al. 2021, Ban et al. 2021, Kendon et al. 2021, Pichelli et al. 2021). Up until now, such studies investigated principally precipitation and have revealed that convection-permitting models (CPMs) show significant advantages in representing complex orographic regions, in producing high-order statistics and predicting events with small temporal and spatial scales compared to RCMs (Gutowski et al. 2020) and reanalysis (Belušić et al. 2018). The international coordinated framework CORDEX Flagship Pilot Study (FPS) on convective phenomena over Europe and the Mediterranean started in 2016, aiming to produce and investigate the first multi-model ensemble of convection permitting simulations (Coppola et al. 2020). There are over 67 individual participants representing 16 modeling groups and five non-hydrostatic regional climate models with a high output temporal resolution of 1 h and a grid spacing around 3 km. A large part of the simulations for the present-day climate driven by ERA-Interim reanalysis (Dee et al. 2011) have been completed and, therefore, will be considered here.

A multi-model and multi-physics ensemble such as the CORDEX FPS gives a great opportunity to examine the added value in two ways; (*i*) to detect the potential added value introduced by CPMs compared to the parent RCMs and reanalysis and (*ii*) to perform in-situ statistical analysis of CPMs with respect to observations. In this study the wind field of the convection permitting CORDEX FPS ensemble has been evaluated for the first time, with focus over the Adriatic region. Accordingly, special attention is given to the comparison of the spatial variability of the wind speed and frequency distribution of wind directions in CPMs and RCMs.

The aim is to inspect the capabilities of CPMs to realistically simulate the small-scale characteristics of the local winds, namely Bora (Grisogono & Belušić 2009) and Sirocco (Pasarić et al. 2007, Horvath et al. 2008), which were not captured well by EURO-CORDEX simulations analyzed in Belušić et al. (2018). It is important to note that Bora and Sirocco winds are driven by two different mechanisms. While Bora is a gusty downslope wind, which experiences a strong influence of the terrain and usually blows perpendicular to the Dinarides, Sirocco is generated by synoptic-scale events and usually parallel to the coastline. The climatology of the present-day Bora wind, which is obtained from observations at meteorological stations (Poje 1992), from satellites (Zecchetto & Cappa 2001), and from simulations (Horvath et al. 2011, Stiperski et al. 2012, Prtenjak et al. 2015), reveals that Bora wind is the strongest, most frequent, and persistent over the northeastern Adriatic (i.e. the region around Trieste and Senj). The main characteristic of the Bora wind is the spatial variation in wind speed (Grisogono & Belušić 2009, Prtenjak et al. 2015) due to the formation of alternating Bora jets and wakes along the coast. The wind speed often reaches severe intensities (i.e. maximum mean hourly northeasterly wind speed >17.0 m/s, Bajić 1989) within the jets. These jets are associated with mountain passes (Kuzmić et al. 2013), which affect the Bora wind duration and strength locally. Contrary to Bora wind, Sirocco is less influenced by the coastal orography. However, it is known that the Sirocco is stronger along the eastern than along the western Adriatic coast, due to the channeling effects of the surrounding mountains (Pasarić et al. 2007). The maximum wind speeds are lower, and the occurrence is less frequent than that of Bora events (Belušić et al. 2018). Characteristics of the Sirocco wind field based on long-term wind observations (Poje 1992, Penzar et al. 2001) suggest that this wind is more frequent and the speeds are higher over the southern Adriatic than those northward of the city of Split.

In order to address the mentioned objectives, we are using an ensemble of 17 CPM simulations, including four different non-hydrostatic models, at ~ 3 km spatial scale, and 14 corresponding RCM simulations including five different models with horizontal resolutions ranging from ~12 km to ~15 km. Moreover, we perform a location-based comparison of the present-day simulations with several observational stations and ERA5 reanalysis data. All simulations and measurements cover a 10 year-long evaluation period extending from 2000 to 2009 with 3-h frequency. Four main points are addressed in this paper, which emphasize the (potential) added value in both the wind speed and wind direction;

(*i*) The enhanced spatial variability,

(*ii*) The possibility of simulating more intense wind speeds,

(*iii*) Having enough skill to replicate the observed wind roses over the complex terrain and the ability of simulating local winds realistically,

(*iv*) The skill in producing temporal correlation coefficients as high as in ERA5 reanalysis.

# 2. DATA AND METHODS

## 2.1. CLIMATE MODEL DATA

A CPM and a parent RCM are limited-area atmosphere-only models, which share the majority of their main physical components, with the main difference in removal of parametrization of deep convection as the spatial resolution increases (Ban et al. 2014). Near-surface wind components at 10 m level were available at hourly frequency for both CPMs and RCMs. However, 3-h data were extracted due to observational measurements availability. Furthermore, all simulations cover a 10 year period, extending from 2000 to 2009. ERA-Interim driven simulations were utilized, therefore, the initial conditions, lateral boundary conditions and sea surface temperatures were derived from the ERA-Interim reanalysis. Furthermore, most of the CPM simulations were run with an intermediate nest (RCM parent domain). Different simulations within the text are identified by Institution abbreviation followed by CPM or RCM name from Table 1.

### 2.1.1. CONVECTION-PERMITTING SIMULATIONS

The CORDEX FPS convection permitting simulations (Coppola et al. 2020), performed over the ALP-3 domain (Fig. 1a) and are used to investigate wind characteristics over the Adriatic. The ALP-3 domain is characterized by a spatial resolution of around 3 km (details can be found in Table 1) and spans an extended Alpine domain from central Italy to northern Germany (4.56 °W–17.4 °E; 37.50 °N–52.63 °N). The Adriatic domain used for the analysis covers the entire Adriatic coastal area and Croatia (12 °E – 17.4 °E, 41°N – 47 °N; Fig. 1b).

Four different models were considered: two flavors of AROME, namely CNRM-AROME41t1 (Fumière et al. 2019) and HCLIM38-AROME (Belušić et al. 2020), two flavors of COSMO, namely COSMO-CLM - Consortium for Small Scale Modeling (Rockel et al. 2008, Baldauf et al. 2011) and COSMO-crCLIM (Leutwyler et al. 2017), RegCM4.7 - Regional Climate Modeling system (Giorgi et al. 2012, Coppola et al 2021) and WRF - the Weather Research and Forecasting modeling system (Powers et al. 2017, Skamarock et al. 2019). Overall, 17 simulations are examined forming a multi-model convection-permitting ensemble (Table 1). A detailed description of each simulation can be found in Ban et al. (2021).

### 2.1.2. REGIONAL CLIMATE SIMULATIONS

In order to inspect the potential added value of a CPM simulation, the parent RCM simulation (Table 1) was also analyzed over the same domain (Fig. 1). The horizontal grid spacing varies between 12 and 15 km depending on the model chosen. Five different models were considered: two flavors of ALADIN, namely CNRM-ALADIN62 (Colin et al. 2010) and HCLIM38-ALADIN (Belušić et al. 2020), COSMO-CLM, RACMO23 (Van Meijgaard et al. 2008), RegCM4.7 and WRF. Mentioned RCMs are implemented by several institutions and, therefore, form an ensemble of 14 RCM simulations. Two COSMO-CLM parent simulations are missing since the corresponding 3-h data was not available at the time this research was conducted, while one COSMO-CLM simulation was conducted as a direct downscaling experiment using ERA-Interim to downscale directly to the 3 km spatial resolution without an intermediate nest.

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**Table 1.** Overview of the analyzed RCM and CPM simulations.

| | CPM | Grid (km) | Parent RCM | Grid (km) | Institution (Abbreviation) |
|---|---|---|---|---|---|
| 1 | CNRM-AROME41t1 | 2.5 | CNRM-ALADIN62 | 12.5 | National Centre for Meteorological Research (CNRM) |
| 2 | HCLIM38-AROME | 2.5 | RACMO23E | 12.5 | Royal Netherlands Meteorological Institute (KNMI) |
| 3 | HCLIM38-AROME | 3 | HCLIM38-ALADIN | 13 | HARMONIE-Climate community: Danish Meteorological Institute and MET Norway and Swedish Meteorological and Hydrological Institute (HCLIMcom) |
| 4 | COSMO-CLM | 3 | / | | Brandenburg University of Technology (BTU) |
| 5 | COSMO-CLM | 3 | COSMO-CLM | 12.5 | Euro-Mediterranean Center on Climate Change (CMCC) |
| 6 | COSMO-crCLIM | 2.2 | COSMO-CLM | 12.5 | Swiss Federal Institute of Technology (ETH) |
| 7 | COSMO-CLM | 3 | / | | Justus-Liebig University of Giessen (JLU) (now University of Kassel (UKa)) |
| 8 | COSMO-CLM | 3 | / | | Karlsruhe Institute of Technology (KIT) |
| 9 | RegCM4.7 | 3 | RegCM4.7 | 12 | International Centre for Theoretical Physics (ICTP) |
| 10 | WRF381BG | 3 | WRF381BG | 15 | Aristotle University of Thessaloniki (AUTH) |
| 11 | WRF381BF | 3 | WRF381BF | 15 | Bjerknes Centre for Climate Research (BCCR) |
| 12 | WRF381BJ | 3 | WRF381BJ | 15 | Center for International Climate Research (CICERO) |
| 13 | WRF381BH | 3 | WRF381BH | 15 | Instituto Dom Luiz (IDL) |
| 14 | WRF381BE | 3 | WRF381BE | 15 | Institut Pierre Simon Laplace (IPSL) |
| 15 | WRF381BI | 3 | WRF381BI | 15 | Universidad de Cantabria (UCAN) |
| 16 | WRF381BD | 3 | WRF381BD | 15 | University of Hohenheim (UHOH) |
| 17 | WRF381BL | 3 | WRF381BL | 15 | Wegener Center for Climate and Global Change (WEGC) |

## 2.2. ERA 5 REANALYSIS

The potential added value of CPMs was also examined in comparison to the global reanalysis. ERA5 (Hersbach et al. 2020) is the fifth generation ECMWF atmospheric reanalysis of the global climate, produced by the Copernicus Climate Change Service (C3S) extending from January 1950 to present. The data covers the Earth on a 0.25° (~30 km) horizontal grid. Although available hourly, we extracted only the estimates of 10-m wind components at 3-h intervals from 2000 to 2009 in order to be analogous with CPMs, RCMs and observed data.

## 2.3. STATION OBSERVATIONS

We used station observations of wind speed and direction to involve another comparison technique. We are aware of the limitations of the observed data, especially when comparing them against gridded climate product. However, no high quality gridded wind observational product is available, for the selected Adriatic domain.

Wind observations at 10-m above ground level from 2000 to 2009 were gathered from different databases in SYNOP format, mostly from Meteorological and Hydrological Service of Croatia (DHMZ), Croatia control (Crocontrol) and a few from NCDC-NOAA (Smith et al. 2011). We considered only stations having more than 70% of 3-h data available in the period of interest. Ultimately, a subset of 16 stations satisfied the criteria for both wind magnitude and direction and were analyzed within the framework of this paper (Fig. 1b). Each of the station time series was linked to the nearest (in longitude and latitude) simulation grid point in order to evaluate the wind climatology.

## 2.4. METHODS

The present-day climate wind evaluation is performed by computing the ensemble mean for the DJF and JJA season for both wind magnitude and normalized wind vector over the domain of interest. Wind vectors are computed using seasonal mean of $u$ and $v$ wind components first. Probability density functions (PDFs) are examined and are complemented by calculating the Perkins skill score (PSS, Perkins et al. 2007), which measures a similarity between two PDFs by computing the common area between them. Afterwards, special attention was given to the upper percentiles. The score presented in Figure 3 shows the frequency distribution of the spatial $95^{th}$ (Q95) percentile. It involves the spatial calculation of the $95^{th}$ percentile (Q95), taking into account the whole domain. Repeating this for each time step over the whole period of interest, we obtained the probability distribution of Q95. Finally, we determined how many times the spatial Q95 is larger than 5 or 15 m/s.

Furthermore, to assess the specific local wind regimes over the Adriatic two directional ranges are analyzed in detail following Belušić et al. (2018) and Belušić Vozila et al. (2019): *i*) perpendicular to the alongshore mountains NNE (22.5°)–ENE (67.5°) and *ii*) parallel with the alongshore mountains ESE (112.5°)–SSE (157.5°), which correspond to Bora and Sirocco directions, respectively. The direction ranges are selected in order to focus on channeling effects of the terrain on both wind types. The Bora/Sirocco events are defined as the occurrence of 3-h wind from NNE to ENE/ESE to SSE. The frequency of a particular wind type is calculated by summarizing how many time steps fell within the selected Bora/Sirocco definition in the analyzed period.

The paper is concluded by computing standard statistical measures in time (i.e. bias, standard deviation and correlation coefficient) with respect to in-situ observations divided in two groups, namely inland stations and coastal stations.

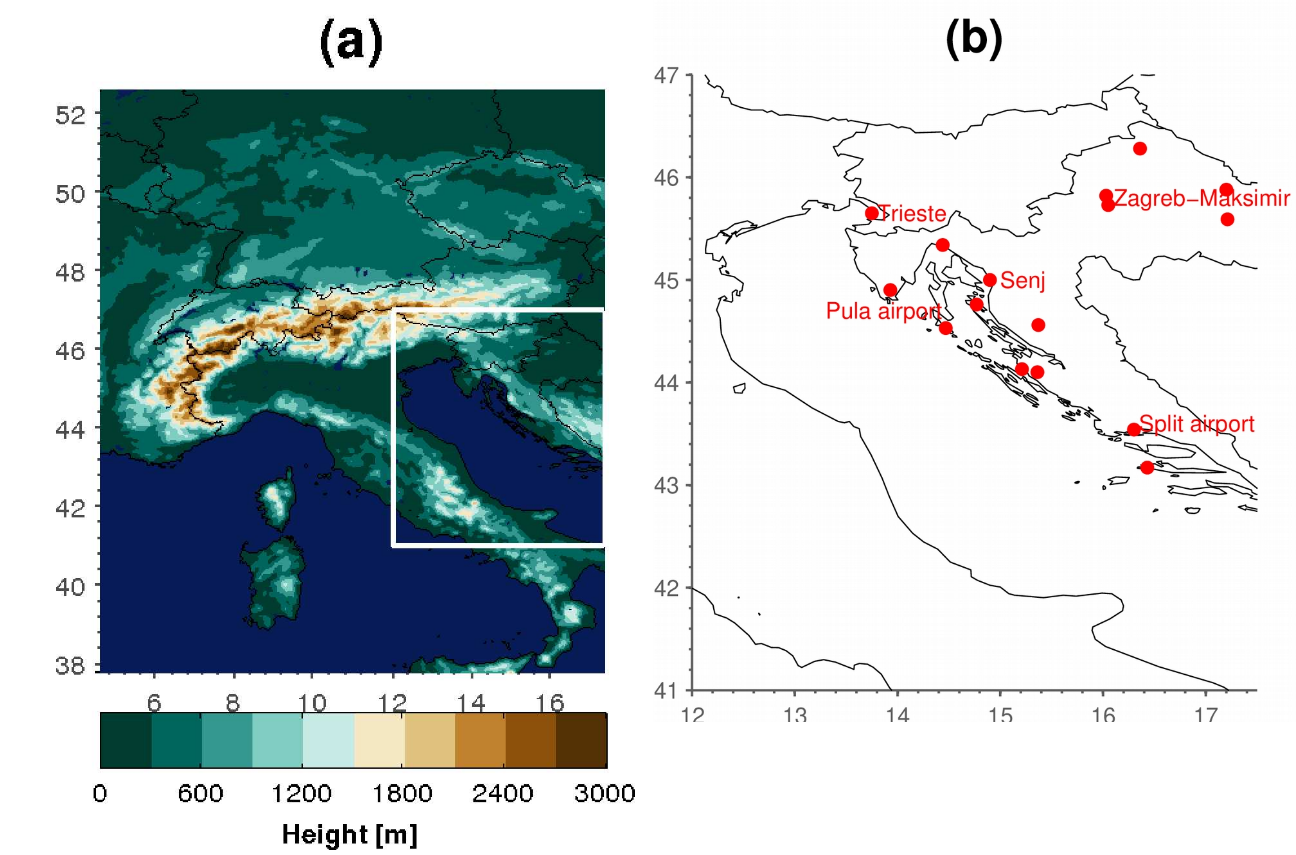



**Figure 1.** a) ALP-3 domain and the Adriatic domain (white box) used in this study. Colors correspond to topographic elevation in meters obtained from ICTP-RegCM4.7 CPM simulation. b) Adriatic domain with stations analyzed in this study in red dots. Names are associated with the stations mentioned in text.

# 3. RESULTS AND DISCUSSION

## 3.1. THE SPATIAL VARIABILITY

Figure 2 displays the seasonal (cold season-DJF) mean wind vectors and scalar wind speeds over the Adriatic for CPM ensemble (a), RCM ensemble (b) and ERA5 reanalysis (c). The DJF season is chosen since it is the windiest season over the Adriatic (Belušić Vozila et al. 2021) with maximum spatial variance calculated from simulations (not shown). The potential added value of dynamical downscaling to finer grid spacing can immediately be recognized from much more detailed structures in the spatial wind patterns (Fig. 2a).

The variability of the wind field over land is largely influenced by fine-scale topography, while the wind field over the open-sea is mostly affected by large-scale atmospheric circulations (Herrmann et al. 2011, Menendez et al. 2014). Following this, the wind field over the Adriatic region experiences the influence of different types of surface. Over the open-sea region, where the driving processes are mainly under the influence of large-scale motions, which are reliably simulated also by coarse resolution simulations (Di Luca et al. 2015), and where the wind field is more uniform, all simulations show similar results. In DJF over the Croatian lowlands, the relatively weak northwesterly

(NW) wind in ERA5 (Fig. 2c) does not deviate significantly from the prevailing wind in RCMs (Fig. 2b). Differences are evident in CPMs (Fig. 2a) in the vicinity of the isolated mountains in the lowlands.

Regardless of the horizontal grid spacing, the coastal region in the eastern Adriatic is characterized by northeasterly (NE) wind of greater intensity. On the other hand, for the wind intensities in the coastal region, where topography plays a significant role in the wind field modifications, refining the grid scale becomes important. Potential added value introduced by CPMs (Fig. 2a) can be seen in much finer wind structures taking into account more variable wind intensity and direction. They are related to the Bora jets, regions with higher wind speed, which are associated with coastal mountain passes, particularly along Velebit Mountain as observed in measurements and case-study simulations (Grisogono & Belušić 2009, Stiperski et al. 2012, Prtenjak et al. 2015). The maximum wind speed associated with the Bora jet in Figure 2a is 11 m/s. On the other hand, these jets are hardly visible in coarser resolution simulations, which have a smaller spread in magnitude (maximum of 8 m/s within the jet in Fig. 2b and 6.5 m/s in Fig. 2 c).

This seasonal wind climatology in Figure 2a is in agreement with the 10-m wind distribution obtained by the numerical weather forecast mode of ALADIN model at 2 km grid spacing in Horvath et al. (2011) and QuikSCAT analysis over Adriatic in Accadia et al. (2007).

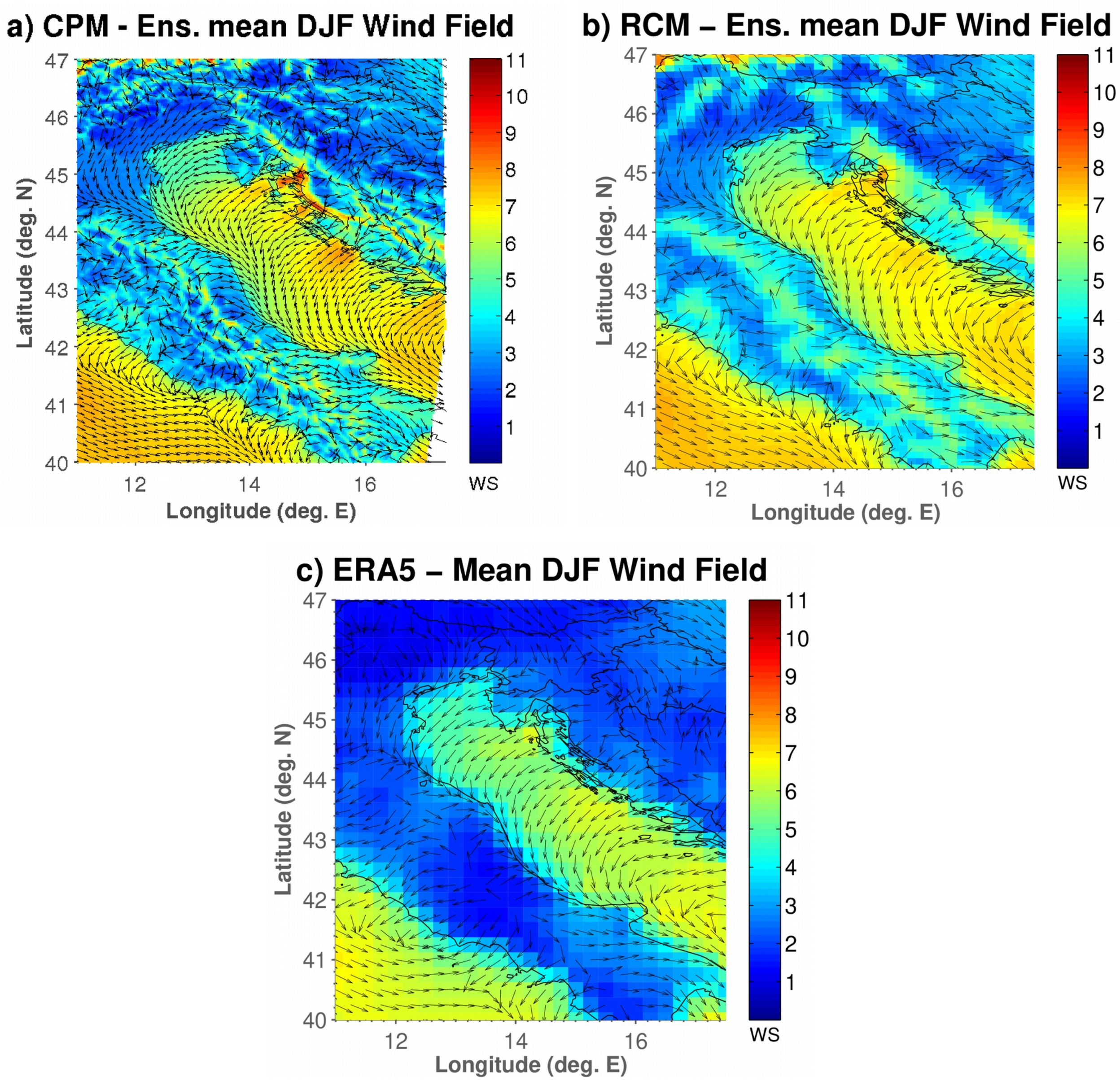



**Figure 2.** Cold season (DJF) spatial mean of wind speed (colors) and normalized wind direction (black arrows) for a) CPM ensemble, b) RCM ensemble, c) ERA5. For the CPM ensemble every 6th, while for the RCM ensemble every 2nd vector is shown.

### 3.2. SEVERE WIND SPEEDS

The indication of potential added value in terms of the seasonal (DJF. JJA) spatial extremes is addressed here. If considering the whole PDF when calculating the PSS, no clear added value of CPMs has been shown. Therefore, we focus only on the strongest winds as explained in section 2.4.

Figure 3 shows the ratio in number of events between CPMs and their parent RCMs, for Q95 larger than 5 m/s (Fig. 3a and c) and 15 m/s (Fig. 3b and d). There is no value for KNMI and HCLIMcom in Figure 3d since those RCMs show zero values larger than 15 m/s in JJA. The Q95 larger than 5 m/s represents 90% of data in all simulations, with almost no differences in the number of events in CPMs and RCMs. Strong wind events (Q95 > 15 m/s) are more frequent in CPMs compared to RCMs (around 1.3 times more frequent in DJF season, and up to 2 times more frequent in JJA season). Those events constitute a small (10% in DJF and <1% in JJA) portion in the whole dataset. Due to the very small portion of the extreme events in JJA, the potential added value is more evident for the cold season. Therefore, strong wind events are more frequent in the cold season and could be much more realistically simulated with CPMs.

This section also shows how different statistical indices can indicate different potential added value depending on which part of the frequency distribution is sampled. That is, higher percentiles (strong winds) of the distribution show a much larger sensitivity to changes in resolution than central moments (moderate winds). Such a sensitivity of the potential added value to the resolution change is also evident for other variables, such as precipitation (Di Luca et al. 2012, Torma et al. 2015, Ban et al. 2021, Ciarlo et al. 2021).

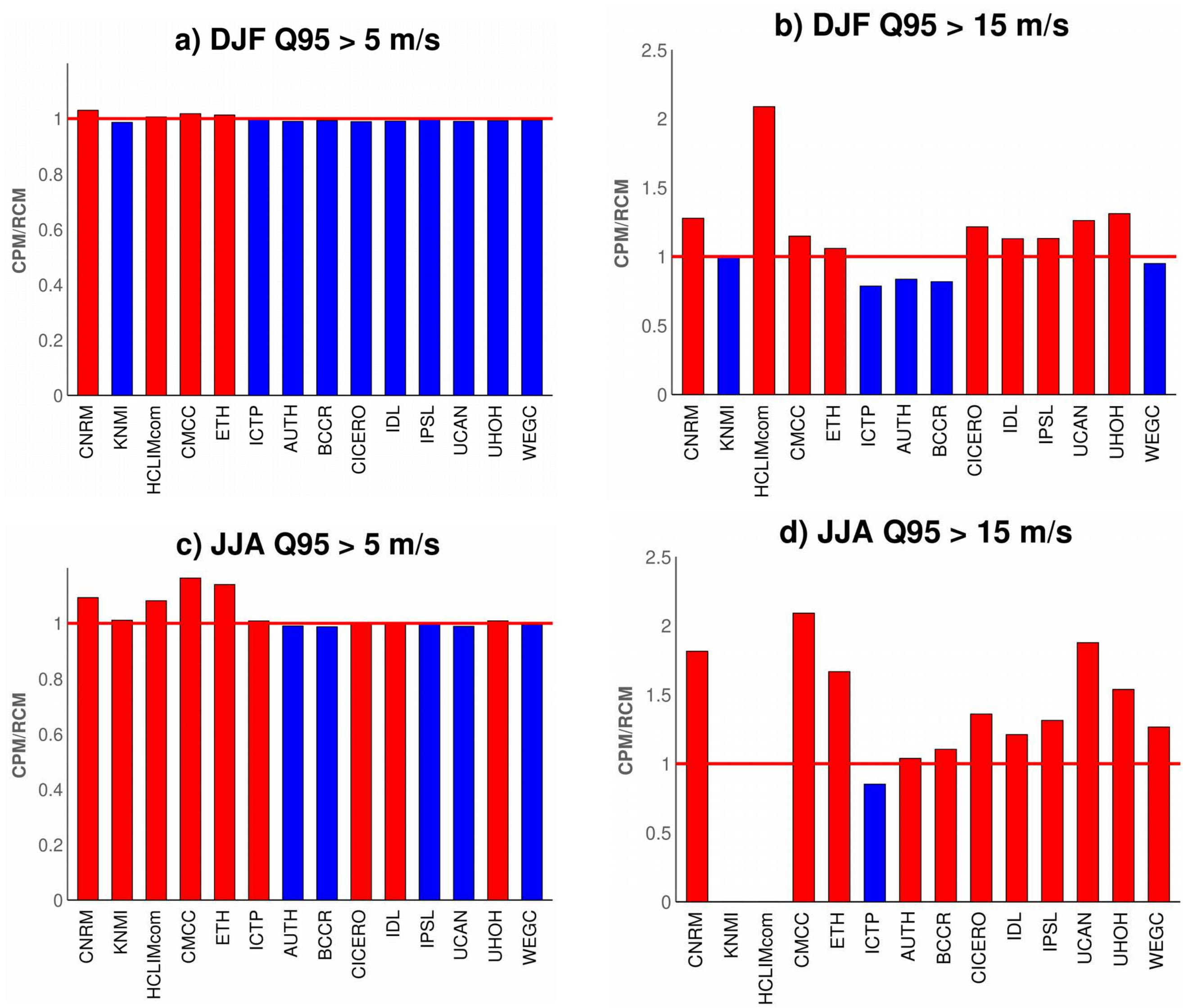



**Figure 3.** Ratio of frequency distribution of spatial Q95 (95th percentile) of the wind speed for all available pairs of CPM-RCM simulations. First row (a, b) cold season (DJF), second row (c, d) warm season (JJA). (a, c) Q95 > 5 m/s, (b, d) Q95 > 15 m/s. Red bars indicate CPM v. RCM ratio larger than 1, while blue bars indicate ratio smaller than 1.

Names in the x-axis represent the Institution which provided both CPM and RCM data (Table 1). There is no value for KNMI and HCLIMcom in Figure 3d since those RCMs show zero values larger than 15 m/s in JJA.

### 3.3. BORA AND SIROCCO

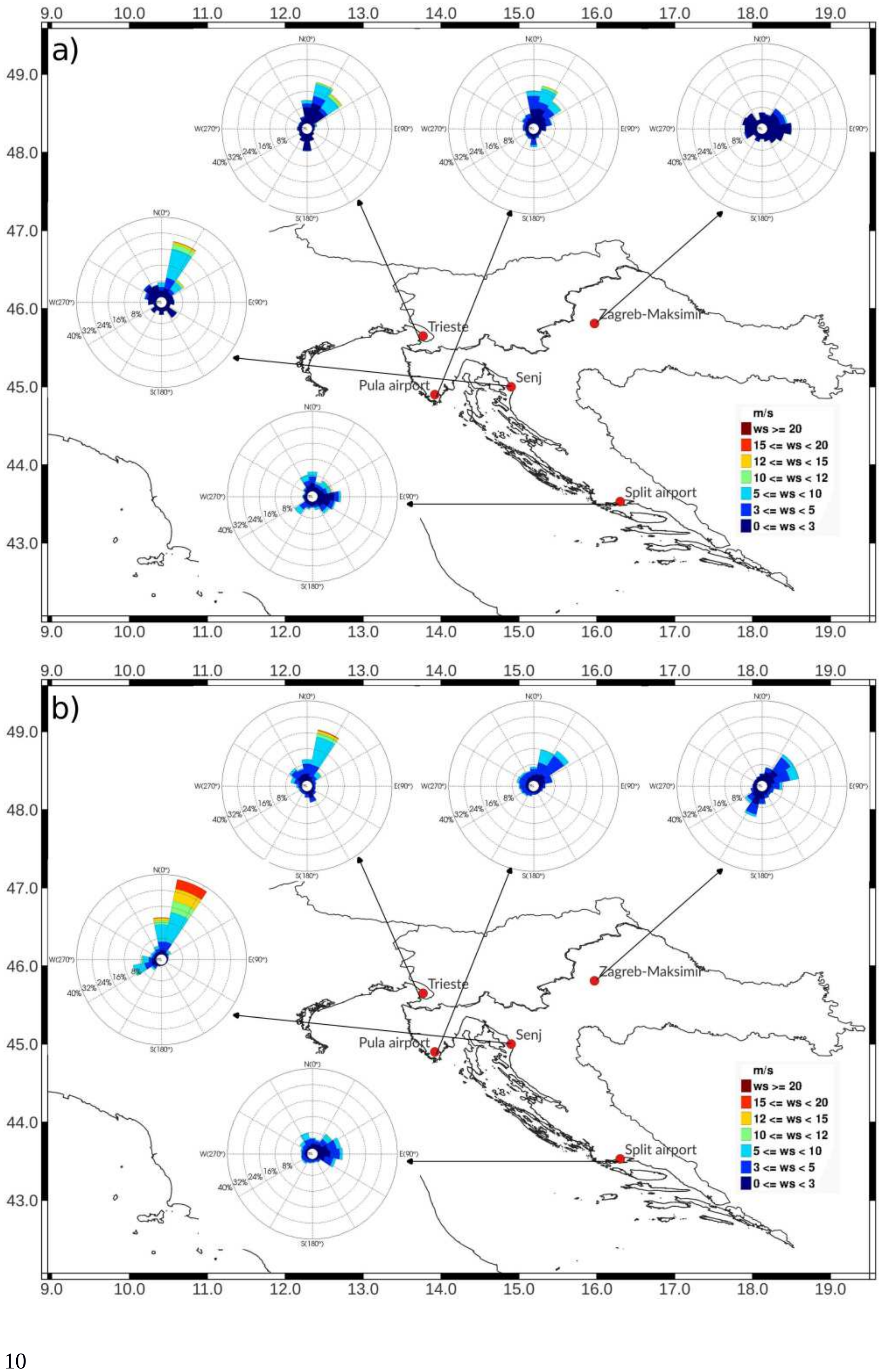
In previous sections, we showed that severe winds, which involve Bora and Sirocco along the Adriatic, can be simulated with more details by CPMs. Here, we compare the simulated wind field to the actual observations. Since different regimes generate wind flow in the coastal and the continental part of the Adriatic region, we do not expect CPMs to have the same skill in simulating the wind field over the entire domain. Wind roses from observational stations (Fig. 4a), CPM ensemble mean (Fig. 4b) and the corresponding RCM ensemble mean (Fig. 4c) are shown for several stations (Fig. 1b; Zagreb-Maksimir – inland station, Pula airport – coastal station in flat terrain, Trieste, Senj and Split airport – three coastal stations in the complex terrain). The former two coastal stations are Bora representatives (e.g. Belušić & Grisogono 2009, Telišman Kuzmić et al. 2013, Prtenjak et al. 2015), while the latter is a Sirocco representative (e.g. Međugorac et al. 2015, Međugorac 2018).

For the inland station (Zagreb-Maksimir), all wind directions are equally represented (~8% each) with the maximum wind speed from 67.5º (NE direction) reaching 9.6 m/s. For the coastal flat part of the Adriatic region (Pula airport) N-NE winds prevail contributing ~48% to the frequency distribution (where 25% is within the defined Bora range). The maximum wind speed is 17 m/s blowing from 30º. Moving to the complex terrain, Bora occurs ~40% of the time at both Trieste and Senj station in the northern Adriatic. The maximum 3-h wind speed at Trieste station is 20 m/s blowing from 50º, while at Senj it is 19.2 m/s blowing from 22.5º. However, it is well-known that the observed wind speed at Senj station should be considerably larger. This issue has previously been addressed by Bencetić Klaić et al. (2009), who show that the location of the observational station is shielded from the Bora directions and therefore underestimates the Bora wind speed. The wind speed observed at the station is underestimated by about 40%, but the wind direction is realistic. Further south (Split airport), Sirocco becomes comparable to Bora in the number of observed events, with Sirocco occurring 13% and Bora 14% of the time. The maximum wind speed still occurs for the Bora wind and equals 23 m/s from 60º, while the maximum wind speed for Sirocco is 10 m/s.

The CPM and RCM ensembles show that for the inland station (Zagreb-Maksimir) all simulations perform well, however, both tend to overestimate the observed wind speed. In the flat coastal terrain (Pula airport) CPM and RCM ensemble correctly simulate the wind speed distribution over all directions. Still, simulations slightly underestimate the frequency of the northerly winds which have the same frequency of occurrence as all other directions together (44% for CPMs and for 38% RCMs compared to the observed 48%).

Moving on to the complex coastal region, the skill of simulating speed and direction distribution in RCMs is reduced. At Trieste station RCMs produce ~30% of Bora events with a maximum of 12 m/s (40% with maximum of 20 m/s is observed), while at Senj station they produce 36% of Bora events with a maximum of 24 m/s (42% with maximum of 19.2 m/s is observed). In contrast, CPMs continue displaying reliable results even here. The maximum wind speed is much more realistic for Trieste (ensemble mean is 19.5 m/s), while the maximum Bora wind speed for Senj seems to be overestimated (ensemble mean is 29 m/s). However, considering the above-mentioned underestimation of the Bora wind speed by 40% at the Senj observational station, the observed maximum Bora speed would reach 27 m/s, thus being much closer to the CPM simulation. The frequency of occurrence of the Bora in CPMs is 30% at Trieste and 50% at Senj station, compared to the observed 40% and 42% respectively.

In southern Adriatic, where Sirocco plays an important role, RCMs can not be taken as representative due to their inability to simulate Sirocco events from the defined angle range (6% compared to the observed 13% in the analyzed period). RCMs tend to simulate an exaggerated number of Bora events with moderate wind speeds along the whole eastern Adriatic coast, including Split airport station (25% of Bora events compared to the observed 14%). Sirocco events in the southern Adriatic were also poorly simulated by the previously examined CORDEX RCM simulations with daily time step (Belušić et al. 2018). CPMs simulate Bora at the Split station well, slightly underestimating the wind speed with the frequency of occurrence of 13%. The representation of both maximum wind speed (ensemble mean is 13 m/s, while 10 m/s is observed) and frequency (10%) for Sirocco is realistic with CPMs. To summarize, CPMs enhance the number of Sirocco events at the expense of Bora compared to RCMs and are hence closer to observations. Accordingly, all these points disclose directly the link between better resolved topography and the representation of the wind.


a)
b)
Trieste
Zagreb-Maksimir
Senj
Pula airport
Split airport
m/s
ws >= 20
15 <= ws < 20
12 <= ws < 15
10 <= ws < 12
5 <= ws < 10
3 <= ws < 5
0 <= ws < 3

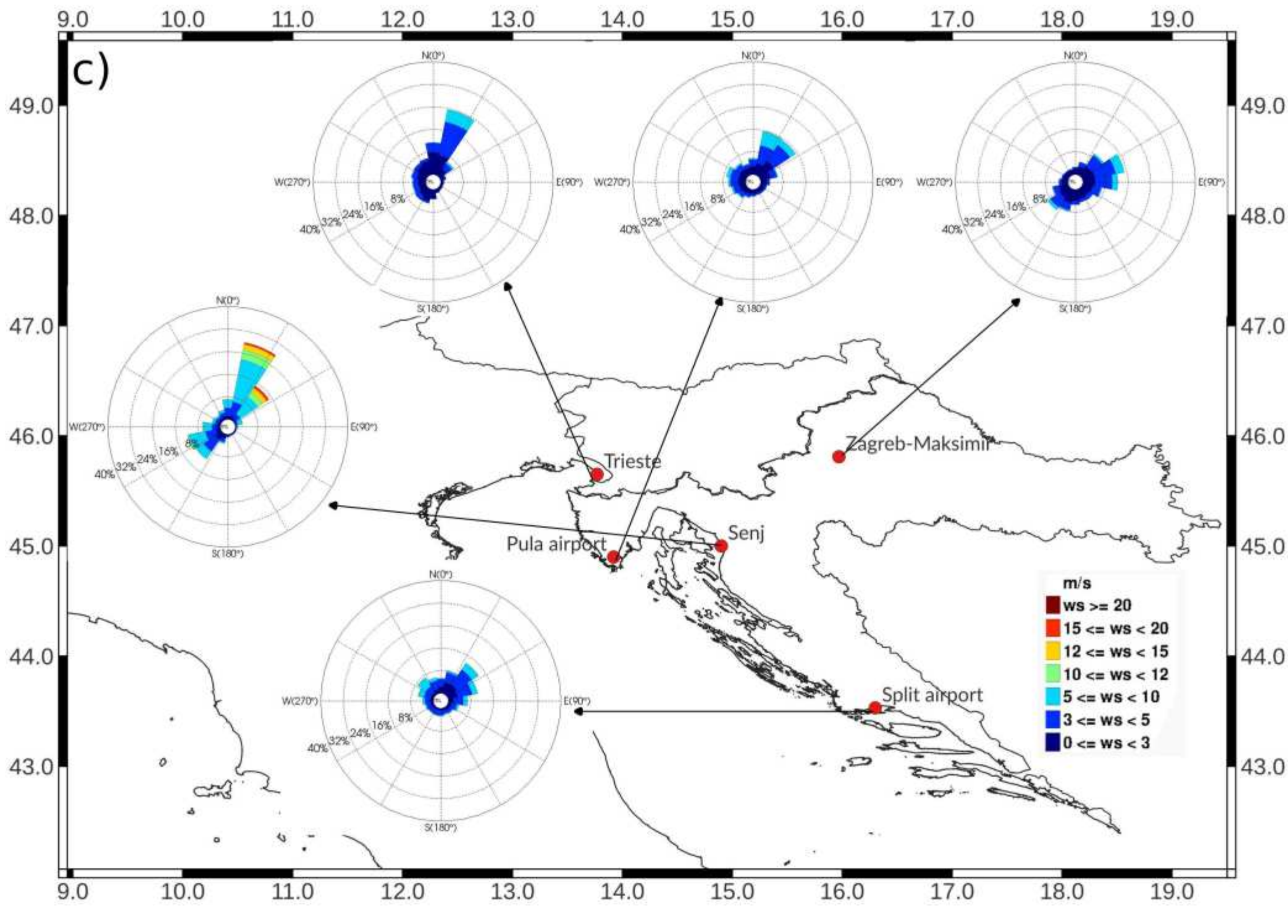



**Figure 4.** Wind roses for stations indicated in Figure 1b over the whole analyzed period. (a) observations (b) CPM ensemble mean, (c) RCM ensemble mean.

Extracting only the direction ranges defined for Bora and Sirocco and focusing on the cold season (DJF) we can inspect the added value in more detail. In Figure 5 we focus on the DJF maximum wind speed for Bora at Trieste station (a) and Sirocco frequencies at Split airport (b). Benefits introduced by CPMs are especially evident for these parameters. The maximum wind speed of DJF Bora events at Trieste station in the observed period is 20 m/s and Bora maximum speed simulated by CPMs is almost perfect, except for WRF simulations, which overestimated the maximum by 20%. On the other hand, RCMs and ERA5 perform similarly and underestimate the maximum wind speed by ~30%.

Sirocco frequencies, defined as strictly along shore in the southern Adriatic, are poorly simulated by RCMs, but CPMs approach close to observations. The underestimation of the number of Sirocco by RCMs (and ERA5) is larger (~50%), compared to Bora (20% shown in Fig. 4). Figure 5b supports the fact that CPMs strongly enhance the number of Sirocco events for all the simulations analyzed. The simulated frequencies come very close to the observations (~1000 events in DJF) except for CNRM-CNRM-AROME41t, KNMI-HCLIM38-AROME and HCLIMcom-HCLIM38-AROME. Those simulations would perform better for Sirocco angle definition starting at ~105º (7º discordance with our definition).

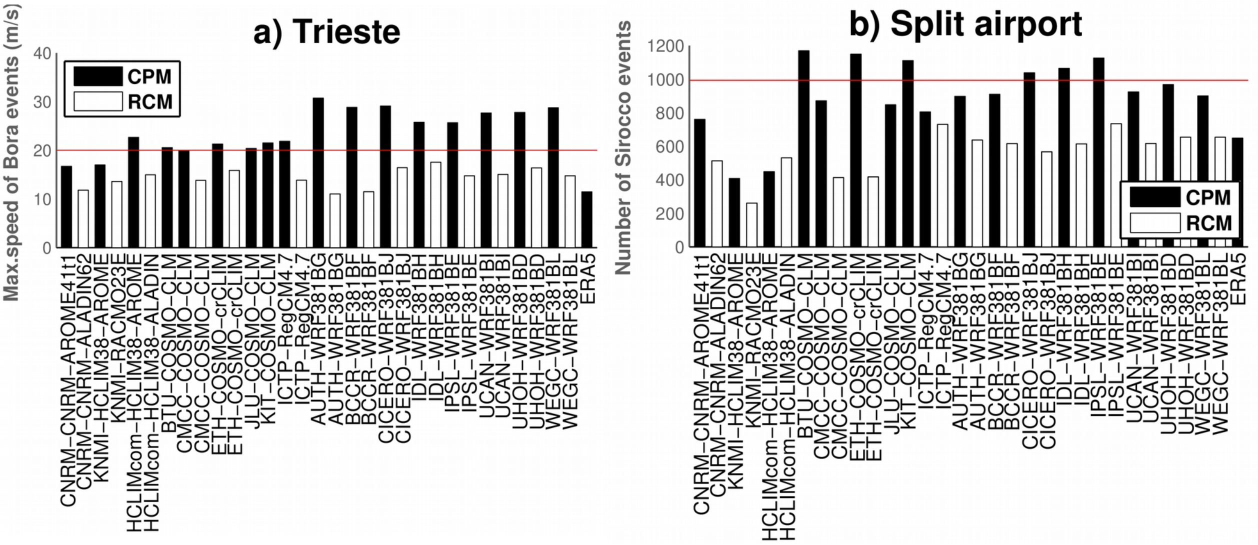



**Figure 5.** Cold season (DJF) Bora (22.5º – 68.5º) maximum wind speed at Trieste station (a) and Sirocco (112.5º -157.5º ) frequencies at Split airport station (b) from all available simulations. Red line represents the observed values.

### 3.5. THE SKILL IN BASIC STATISTICAL MEASURES

Standard statistical measures for all available simulations and for all analyzed stations are shown in Figure 6. Three values correspond to each simulation (bias in red, normalized standard deviation in green and correlation coefficient in blue), while each box-plot contains the values from all the stations in the group (5 inland stations and 11 coastal stations). Numbers on the x-axis indicate CPMs and correspond to the first column in Table 1. Corresponding RCMs are shaded in gray.

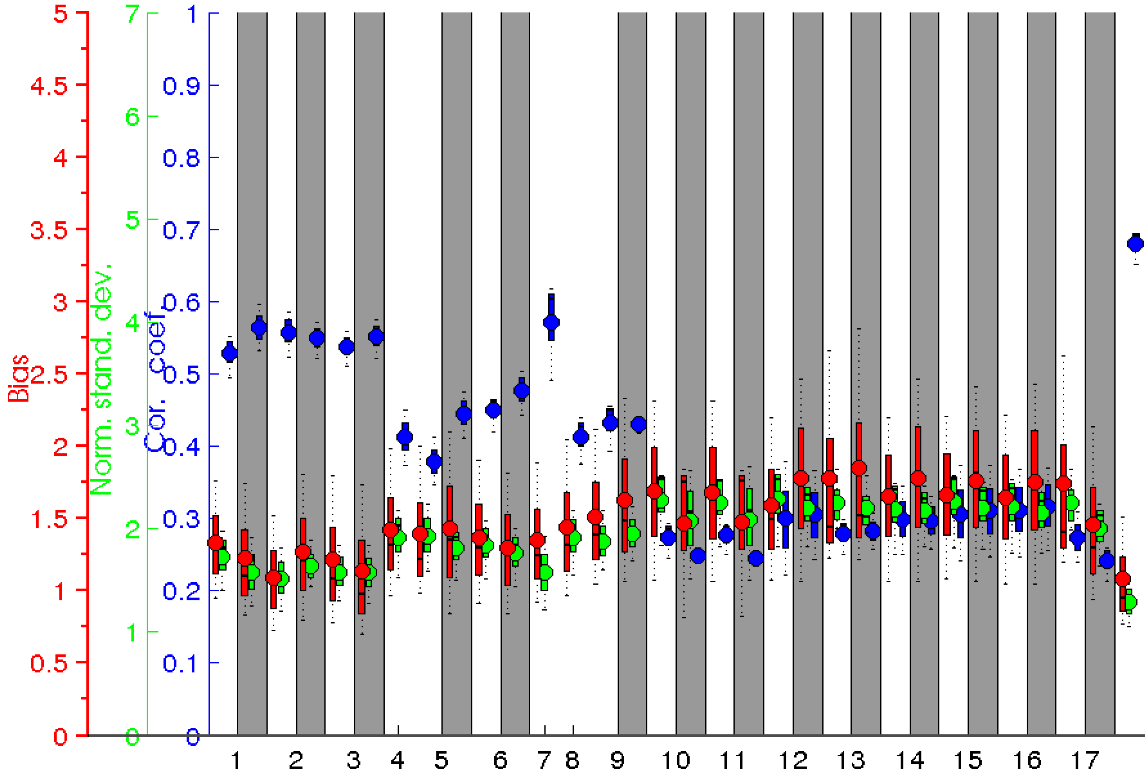
We can notice immediately that each CPM is strongly influenced by its parent RCM. If the RCM does not perform well, there are low chances that CPM will be excellent. It is important to note that this implies that here the choice of resolution affects the final results much less than the choice of particular CPM. This was also true for coarse (50 km) and fine (12 km) resolution RCMs in Belušić et al. (2018).

The difference between inland and coastal regions is in the larger spread among the stations for the latter for the particular statistical parameter. Grouping all the available stations for each terrain type (Fig. 6), the general picture is as follows. Most of the biases over the inland stations are close to zero or positive, in the range of 0–2 m/s (Fig. 6a), indicating a slight wind speed overestimation in the simulations, as we already indicated in section 3.3. Furthermore, the maximum biases in the coastal region with the complex terrain are two times larger than the other maximum biases, ranging from 1–4 m/s, indicating also a large spread of biases among stations. The simulated standard deviation for inland stations (Fig. 6a) usually follows the observed one very well, while in the complex terrain (Fig. 6b), where the wind intensity is high, the simulated standard deviation is up to 6 times larger than the observed one (depending on the simulation and station chosen). Summarizing, higher moments (i.e. standard deviation) of the distribution are worse simulated than central moments (i.e. mean) for both CPMs and RCMs. The presented comparison between inland and coastal station agrees with Obermann et al. (2016) and Belušić et al. (2018). However, the exact values should be interpreted with caution, since the in-situ observations are not necessarily entirely representative for the gridded climate output.

Even if climate simulations with CPMs and RCMs are not primarily designed to exactly follow the development of weather events, some members from the analyzed ensemble manage to follow the observed time series very accurately regardless of the internal variability inside the domain (CNRM-CNRM-AROME41t1, KNMI-HCLIM38-AROME, HCLIMcom-HCLIM38-AROME). As expected, the ERA5 reanalysis (last blue value in Fig. 6) usually has the largest temporal correlation coefficient at all analyzed stations, since a large amount of observational data is assimilated, but it has lower standard deviation due to the resolution limitations.

From the CORDEX FPS ensemble, the CPM simulations from 1 to 3 (CNRM-CNRM-AROME41t1, KNMI-HCLIM38-AROME, HCLIMcom-HCLIM38-AROME), and consequently their parent RCM simulations, appear to best fit the observations at all available stations, having the smallest biases, being the closest to the normalized standard deviation, and having the greatest temporal correlation coefficient (very close to the one obtained from ERA5). On the other hand, the simulations between lines 10 and 17 (WRF) have the poorest performance; larger biases for coastal stations, quite large normalized standard deviation and very low temporal correlation coefficients.

## a) Inland stations (5)




## b) Coastal stations (11)

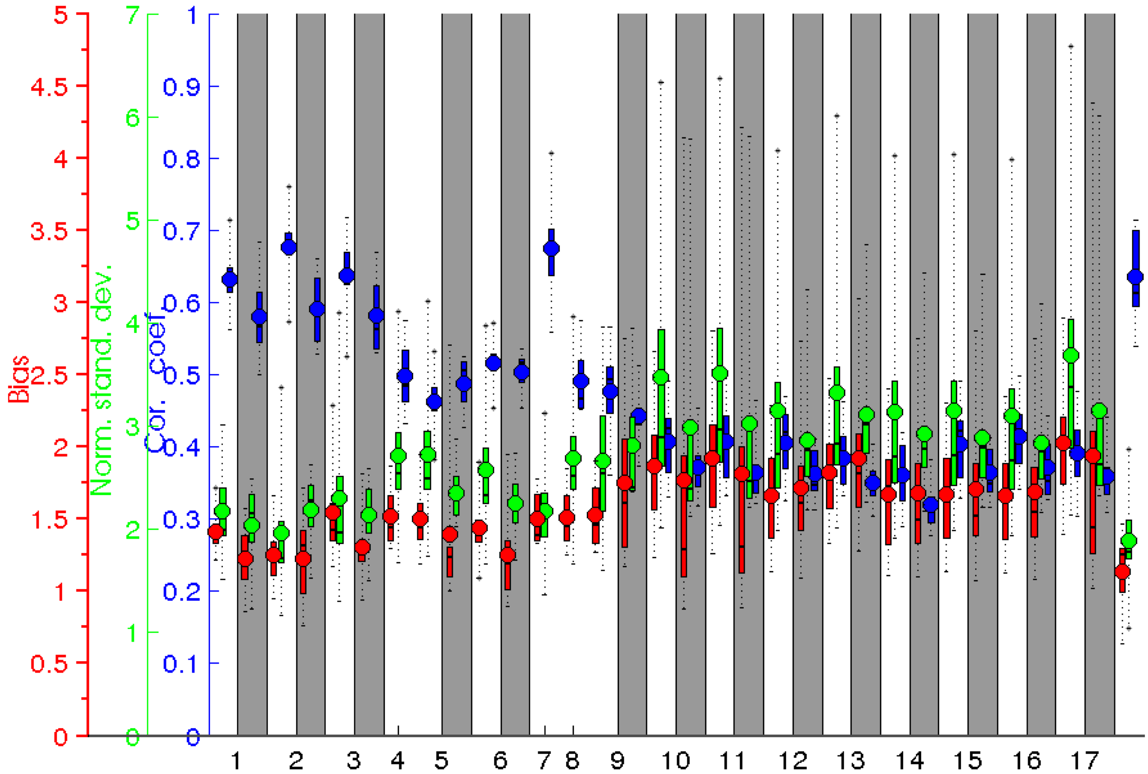


**Figure 6**. Standard statistical measures for all available simulations and for all analyzed stations. Three values correspond to each simulation (bias in red, normalized standard deviation in green and correlation coefficient in blue), while each box-plot contains the values from all the stations in the group (5 inland stations and 11 coastal stations). Numbers on the x-axis indicate CPMs and correspond to the first column in Table 1. Corresponding RCMs are shaded in gray. The last group of values is for ERA5.

## 4. SUMMARY AND CONCLUSIONS

Studies trying to validate the CPMs downscaling technique are essential to highlight the importance of developing CPMs in the future and the use of their products. In this study, the main goal was to objectively assess the (potential) added value obtained by downscaling RCMs to CPMs in terms of the wind field over the Adriatic domain. This article concentrated on 3-h wind obtained from 17 CPMs and 14 RCMs in the period 2000-2009. We show where and with respect to which climate statistics CPMs can produce more skillful results than RCMs. In general, results tend to confirm the advantages of using high-resolution CPMs and the conclusions based on four points proposed in the introduction are as follows:

- *The enhanced spatial variability.*
  CPMs display fine spatial variability that is absent in coarser RCMs or reanalysis, leading to a larger spread in intensities, which allows for capturing more extreme events. Much finer wind structures account for more variable wind intensity and direction. They are especially evident over the entire mountainous ranges along the coastline and in the vicinity of the isolated mountains in the lowlands. This is highly important for the realistic simulation of severe wind formations such as Bora jets.

- *The possibility of simulating more intense wind speeds.*
  Severe wind events are mostly associated with the Bora wind in the cold season. Therefore, potential added value is higher in cold season compared to warm season due to the proportion of severe wind events. The results have shown that severe winds are more frequent and could be much more realistically simulated in high-resolution dataset. It is important to note that intense wind events show much larger sensitivity to changes in resolution than low and moderate wind speeds.

- *Having enough skill to replicate the observed wind roses over the complex terrain and the ability of simulating local winds realistically.*
  Both CPMs and RCMs perform quite well in the flat terrain. In regions with complex topography, the orographic forcing emphasizes the added value of CPMs: RCMs lose the skill in simulating both the wind speed and direction distribution, while CPMs keep the reliable results. The main benefit of using CPMs is detected for Bora maximum wind speeds in the northern Adriatic and for Sirocco frequencies in the southern Adriatic. This discloses directly the link between better resolved topography and the representation of the wind.
- *The skill in producing temporal correlation coefficient as high as in ERA5 reanalysis.*
  Even if climate simulations with CPMs and RCMs are not primarily designed to exactly follow the development of weather events, the assessment of the correlation coefficient showed that some of them manage to fit accurately with the observed time series. We noticed that the choice of resolution (CPM or RCM) affects the final results much less than the choice of the particular CPM. Simulations that showed superior skill in terms of standard statistical scores in time are CNRM-CNRM-AROME41t1, KNMI-HCLIM38-AROME and HCLIMcom-HCLIM38-AROME.

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## Statements and Declarations

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**Competing Interests**

The authors have no relevant financial or non-financial interests to disclose.

**Author Contributions**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Andreina Belušić Vozila. The first draft of the manuscript was written by Andreina Belušić Vozila and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Data availability**

The datasets analyzed during the current study are available via the data exchange infrastructure and services provided by the Jülich Supercomputing Centre, Germany, as part of the Helmholtz Data Federation initiative.

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