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

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1 **Evaluation of the near-surface wind field over the Adriatic region: Local wind characteristics**
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57 **ABSTRACT**

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

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

75 1. INTRODUCTION

76 Evaluation of the wind field over complex terrain provides an excellent opportunity to assess the reliability of
77 the climate model simulations. However, it is a challenging task due to the limited accessibility of observational data
78 and high variability in both speed and direction. Consequently, extensive studies comparing the modeled and observed
79 climate characteristics of the wind field over particular parts of the Mediterranean region, where winds are strongly
80 affected by topography (e.g. Ulbrich et al. 2012), are still rare (Obermann et al. 2016, Bonaldo et al. 2017, Belušić et al.
81 2018), especially on a sub-daily scale. However, sub-daily wind data is crucial in detecting the most severe wind events.
82 Therefore, the evaluation of very high-resolution climate models, in coastal regions and over complex terrain such as
83 the Adriatic, can reveal whether they achieve a good representation of small-scale topographic features and hence more
84 details in dynamical aspects. Moreover, the evaluation of the wind for the present climate is needed for building
85 confidence in wind field projections over future decades.

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

98 Recently, an increasing number of studies show improvements in performances, when the grid spacing is
99 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.
100 2021, Kendon et al. 2021, Pichelli et al. 2021). Up until now, such studies investigated principally precipitation and
101 have revealed that convection-permitting models (CPMs) show significant advantages in representing complex
102 orographic regions, in producing high-order statistics and predicting events with small temporal and spatial scales
103 compared to RCMs (Gutowski et al. 2020) and reanalysis (Belušić et al. 2018). The international coordinated
104 framework CORDEX Flagship Pilot Study (FPS) on convective phenomena over Europe and the Mediterranean started
105 in 2016, aiming to produce and investigate the first multi-model ensemble of convection permitting simulations
106 (Coppola et al. 2020). There are over 67 individual participants representing 16 modeling groups and five non-
107 hydrostatic regional climate models with a high output temporal resolution of 1 h and a grid spacing around 3 km. A
108 large part of the simulations for the present-day climate driven by ERA-Interim reanalysis (Dee et al. 2011) have been
109 completed and, therefore, will be considered here.

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

116 The aim is to inspect the capabilities of CPMs to realistically simulate the small-scale characteristics of the
117 local winds, namely Bora (Grisogono & Belušić 2009) and Sirocco (Pasarić et al. 2007, Horvath et al. 2008), which
118 were not captured well by EURO-CORDEX simulations analyzed in Belušić et al. (2018). It is important to note that
119 Bora and Sirocco winds are driven by two different mechanisms. While Bora is a gusty downslope wind, which
120 experiences a strong influence of the terrain and usually blows perpendicular to the Dinarides, Sirocco is generated by
121 synoptic-scale events and usually parallel to the coastline. The climatology of the present-day Bora wind, which is
122 obtained from observations at meteorological stations (Poje 1992), from satellites (Zecchetto & Cappa 2001), and from
123 simulations (Horvath et al. 2011, Stiperski et al. 2012, Prtenjak et al. 2015), reveals that Bora wind is the strongest,
124 most frequent, and persistent over the northeastern Adriatic (i.e. the region around Trieste and Senj). The main
125 characteristic of the Bora wind is the spatial variation in wind speed (Grisogono & Belušić 2009, Prtenjak et al. 2015)
126 due to the formation of alternating Bora jets and wakes along the coast. The wind speed often reaches severe intensities
127 (i.e. maximum mean hourly northeasterly wind speed >17.0 m/s, Bajić 1989) within the jets. These jets are associated
128 with mountain passes (Kuzmić et al. 2013), which affect the Bora wind duration and strength locally. Contrary to Bora
129 wind, Sirocco is less influenced by the coastal orography. However, it is known that the Sirocco is stronger along the
130 eastern than along the western Adriatic coast, due to the channeling effects of the surrounding mountains (Pasarić et al.
131 2007). The maximum wind speeds are lower, and the occurrence is less frequent than that of Bora events (Belušić et al.
132 2018). Characteristics of the Sirocco wind field based on long-term wind observations (Poje 1992, Penzar et al. 2001)

133 suggest that this wind is more frequent and the speeds are higher over the southern Adriatic than those northward of the
134 city of Split.

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

142 (i) The enhanced spatial variability,

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

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

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

147 2. DATA AND METHODS

148 2.1. CLIMATE MODEL DATA

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

158 2.1.1. CONVECTION-PERMITTING SIMULATIONS

159 The CORDEX FPS convection permitting simulations (Coppola et al. 2020), performed over the ALP-3 domain (Fig.
160 1a) and are used to investigate wind characteristics over the Adriatic. The ALP-3 domain is characterized by a spatial
161 resolution of around 3 km (details can be found in Table 1) and spans an extended Alpine domain from central Italy to
162 northern Germany (4.56°W – 17.4°E ; 37.50°N – 52.63°N). The Adriatic domain used for the analysis covers the entire
163 Adriatic coastal area and Croatia (12°E – 17.4°E , 41°N – 47°N ; Fig. 1b).

164 Four different models were considered: two flavors of AROME, namely CNRM-AROME41t1 (Fumière et al.
165 2019) and HCLIM38-AROME (Belušić et al. 2020), two flavors of COSMO, namely COSMO-CLM - Consortium for
166 Small Scale Modeling (Rockel et al. 2008, Baldauf et al. 2011) and COSMO-crCLIM (Leutwyler et al. 2017),
167 RegCM4.7 - Regional Climate Modeling system (Giorgi et al. 2012, Coppola et al 2021) and WRF - the Weather
168 Research and Forecasting modeling system (Powers et al. 2017, Skamarock et al. 2019). Overall, 17 simulations are
169 examined forming a multi-model convection-permitting ensemble (Table 1). A detailed description of each simulation
170 can be found in Ban et al. (2021).

171 2.1.2. REGIONAL CLIMATE SIMULATIONS

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

181 **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)

182 **2.2. ERA 5 REANALYSIS**

183 The potential added value of CPMs was also examined in comparison to the global reanalysis. ERA5 (Hersbach et al.
184 2020) is the fifth generation ECMWF atmospheric reanalysis of the global climate, produced by the Copernicus Climate
185 Change Service (C3S) extending from January 1950 to present. The data covers the Earth on a 0.25° (~30 km)
186 horizontal grid. Although available hourly, we extracted only the estimates of 10-m wind components at 3-h intervals
187 from 2000 to 2009 in order to be analogous with CPMs, RCMs and observed data.

188 **2.3. STATION OBSERVATIONS**

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

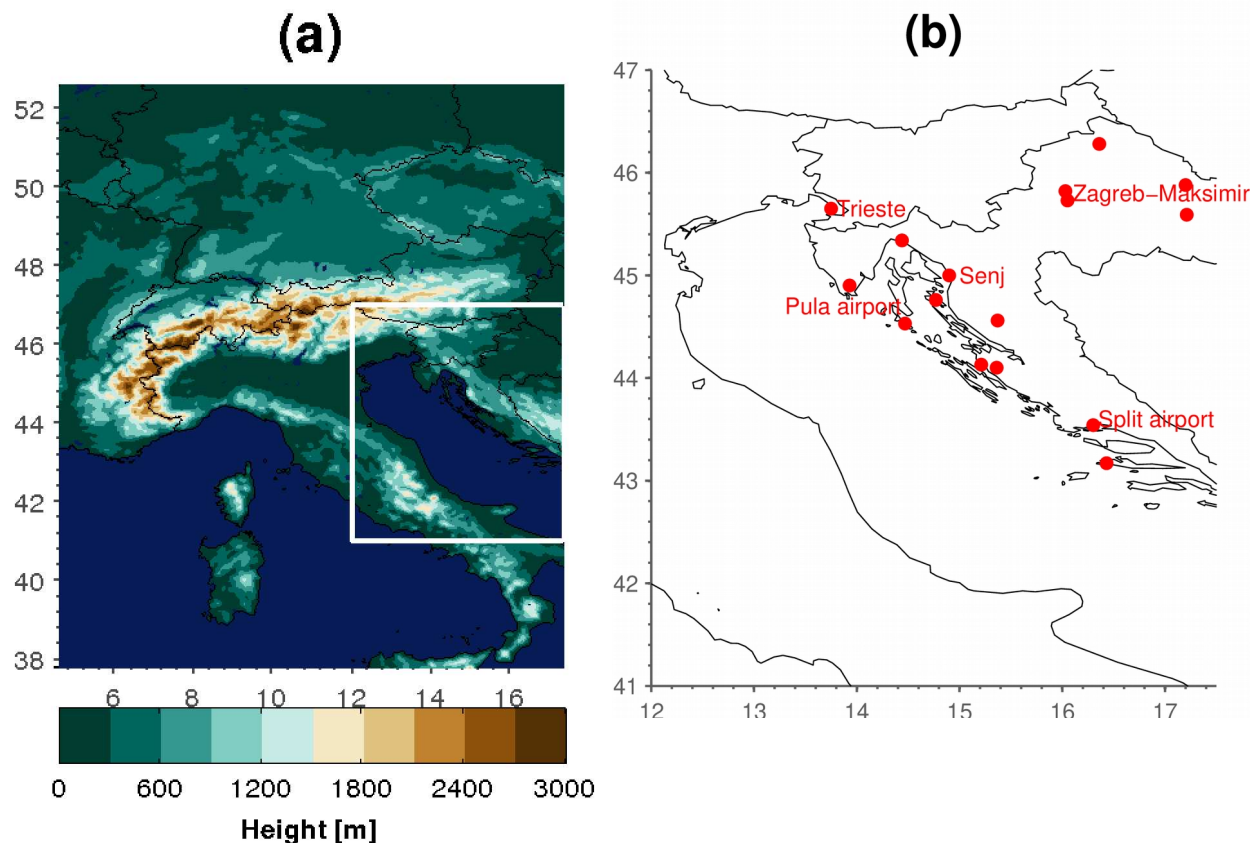
192 Wind observations at 10-m above ground level from 2000 to 2009 were gathered from different databases in
193 SYNOP format, mostly from Meteorological and Hydrological Service of Croatia (DHMZ), Croatia control
194 (Crocontrol) and a few from NCDC-NOAA (Smith et al. 2011). We considered only stations having more than 70% of
195 3-h data available in the period of interest. Ultimately, a subset of 16 stations satisfied the criteria for both wind
196 magnitude and direction and were analyzed within the framework of this paper (Fig. 1b). Each of the station time series
197 was linked to the nearest (in longitude and latitude) simulation grid point in order to evaluate the wind climatology.

198 **2.4. METHODS**

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

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

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



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

221 3. RESULTS AND DISCUSSION

222 3.1. THE SPATIAL VARIABILITY

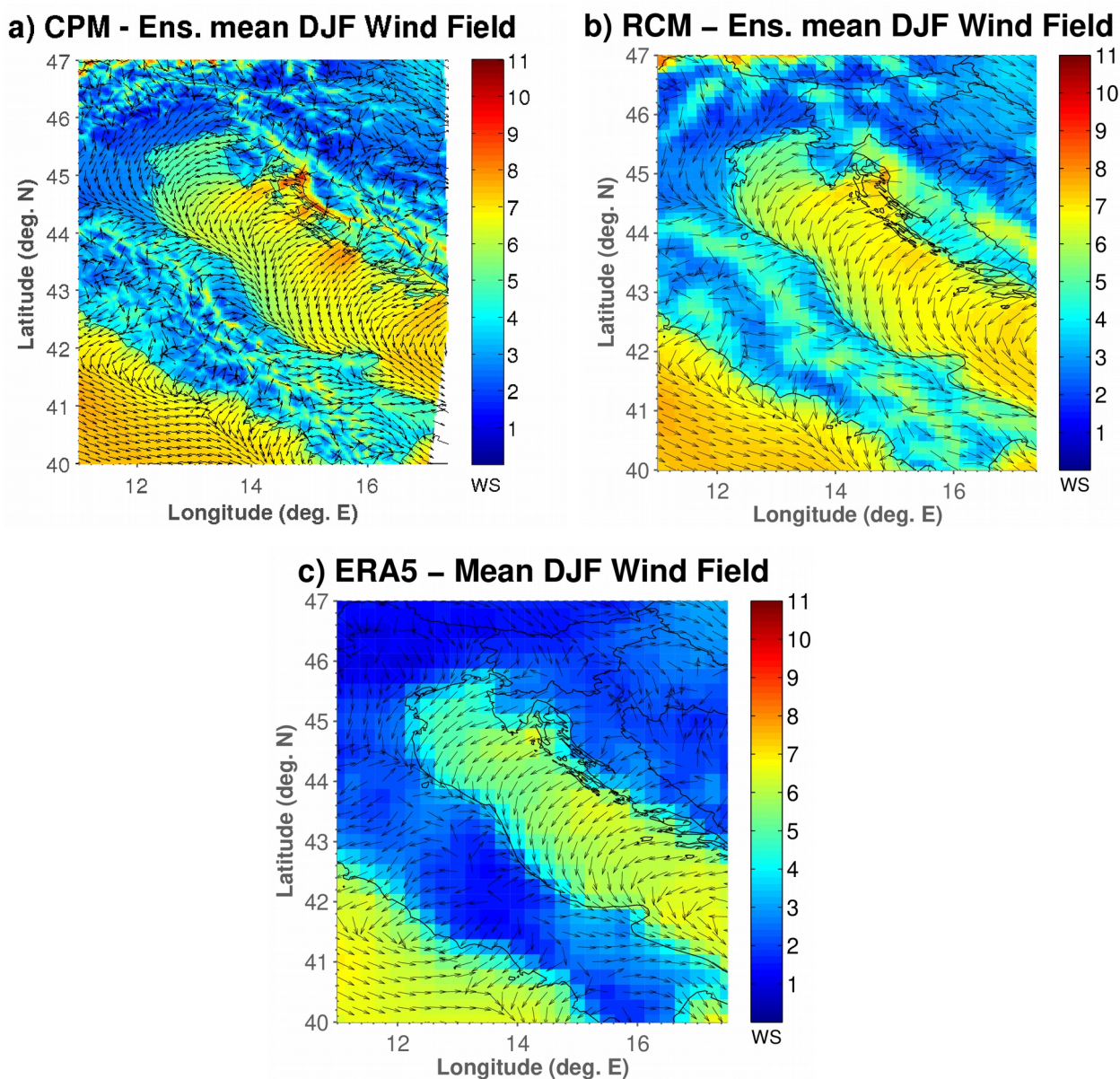
223 Figure 2 displays the seasonal (cold season-DJF) mean wind vectors and scalar wind speeds over the Adriatic for CPM
 224 ensemble (a), RCM ensemble (b) and ERA5 reanalysis (c). The DJF season is chosen since it is the windiest season
 225 over the Adriatic (Belušić Vozila et al. 2021) with maximum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

228 The variability of the wind field over land is largely influenced by fine-scale topography, while the wind field
 229 over the open-sea is mostly affected by large-scale atmospheric circulations (Herrmann et al. 2011, Menendez et al.
 230 2014). Following this, the wind field over the Adriatic region experiences the influence of different types of surface.
 231 Over the open-sea region, where the driving processes are mainly under the influence of large-scale motions, which are
 232 reliably simulated also by coarse resolution simulations (Di Luca et al. 2015), and where the wind field is more
 233 uniform, all simulations show similar results. In DJF over the Croatian lowlands, the relatively weak northwesterly

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

236 Regardless of the horizontal grid spacing, the coastal region in the eastern Adriatic is characterized by
 237 northeasterly (NE) wind of greater intensity. On the other hand, for the wind intensities in the coastal region, where
 238 topography plays a significant role in the wind field modifications, refining the grid scale becomes important. Potential
 239 added value introduced by CPMs (Fig. 2a) can be seen in much finer wind structures taking into account more variable
 240 wind intensity and direction. They are related to the Bora jets, regions with higher wind speed, which are associated
 241 with coastal mountain passes, particularly along Velebit Mountain as observed in measurements and case-study
 242 simulations (Grisogono & Belušić 2009, Stiperski et al. 2012, Prtenjak et al. 2015). The maximum wind speed
 243 associated with the Bora jet in Figure 2a is 11 m/s. On the other hand, these jets are hardly visible in coarser resolution
 244 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.
 245 2 c).

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



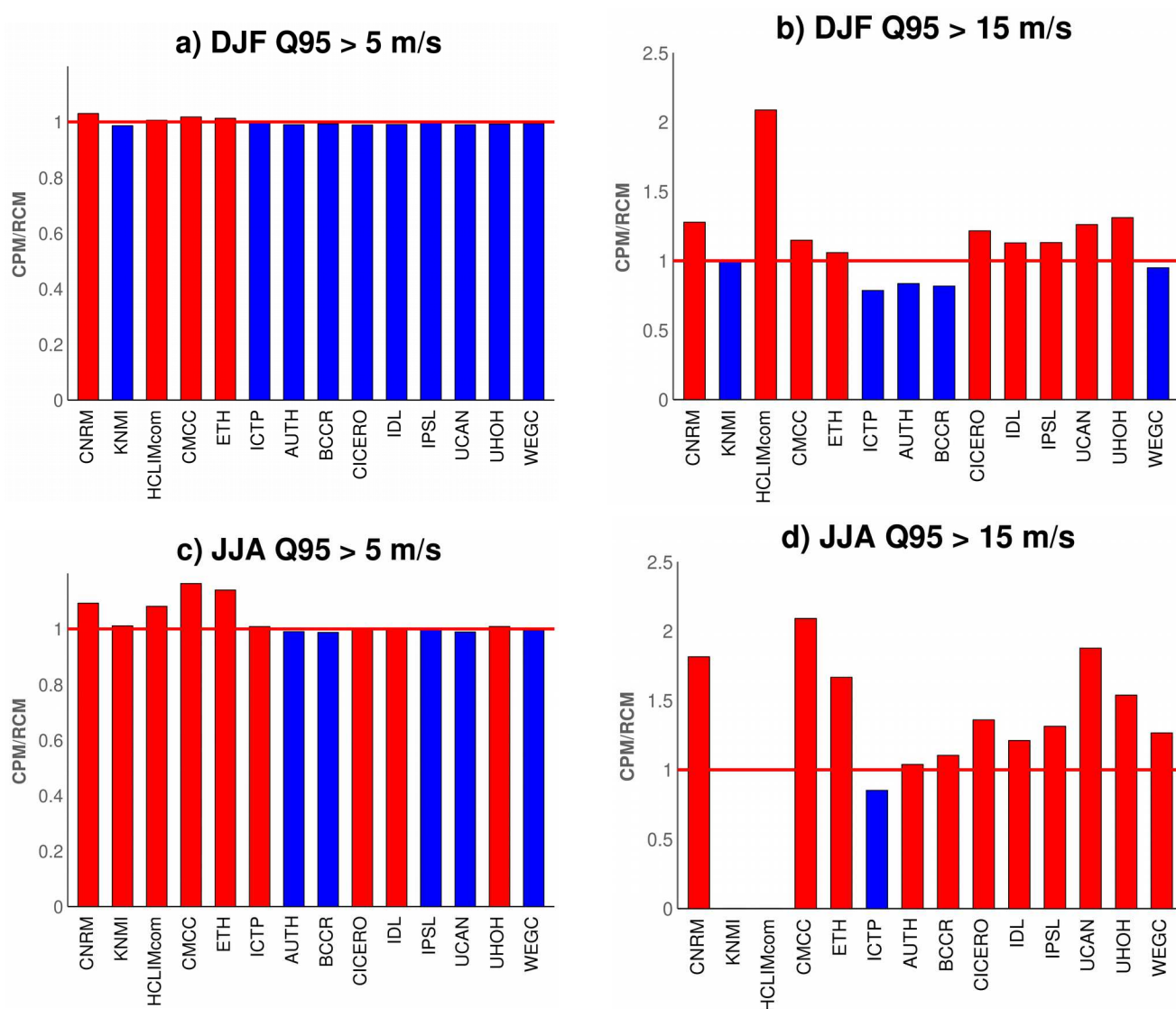
249 **Figure 2.** Cold season (DJF) spatial mean of wind speed (colors) and normalized wind direction (black arrows) for a)
 250 CPM ensemble, b) RCM ensemble, c) ERA5. For the CPM ensemble every 6th, while for the RCM ensemble every 2nd
 251 vector is shown.

252 **3.2. SEVERE WIND SPEEDS**

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

256 Figure 3 shows the ratio in number of events between CPMs and their parent RCMs, for Q95 larger than 5 m/s
 257 (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
 258 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
 259 almost no differences in the number of events in CPMs and RCMs. Strong wind events (Q95 > 15 m/s) are more
 260 frequent in CPMs compared to RCMs (around 1.3 times more frequent in DJF season, and up to 2 times more frequent
 261 in JJA season). Those events constitute a small (10% in DJF and <1% in JJA) portion in the whole dataset. Due to the
 262 very small portion of the extreme events in JJA, the potential added value is more evident for the cold season.
 263 Therefore, strong wind events are more frequent in the cold season and could be much more realistically simulated with
 264 CPMs.

265 This section also shows how different statistical indices can indicate different potential added value depending
 266 on which part of the frequency distribution is sampled. That is, higher percentiles (strong winds) of the distribution
 267 show a much larger sensitivity to changes in resolution than central moments (moderate winds). Such a sensitivity of
 268 the potential added value to the resolution change is also evident for other variables, such as precipitation (Di Luca et al.
 269 2012, Torma et al. 2015, Ban et al. 2021, Ciarlo et al. 2021).



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

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

275 3.3. BORA AND SIROCCO

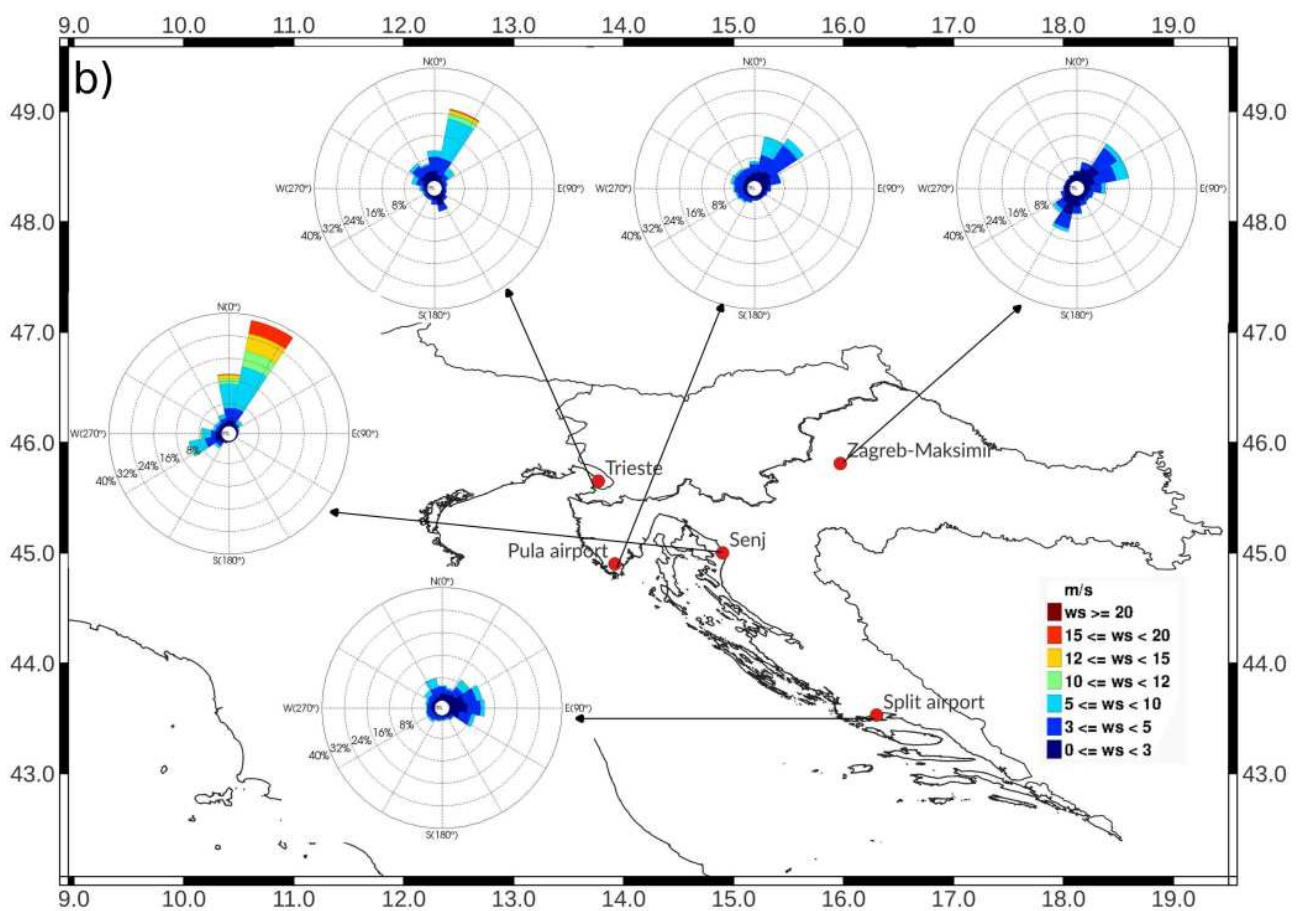
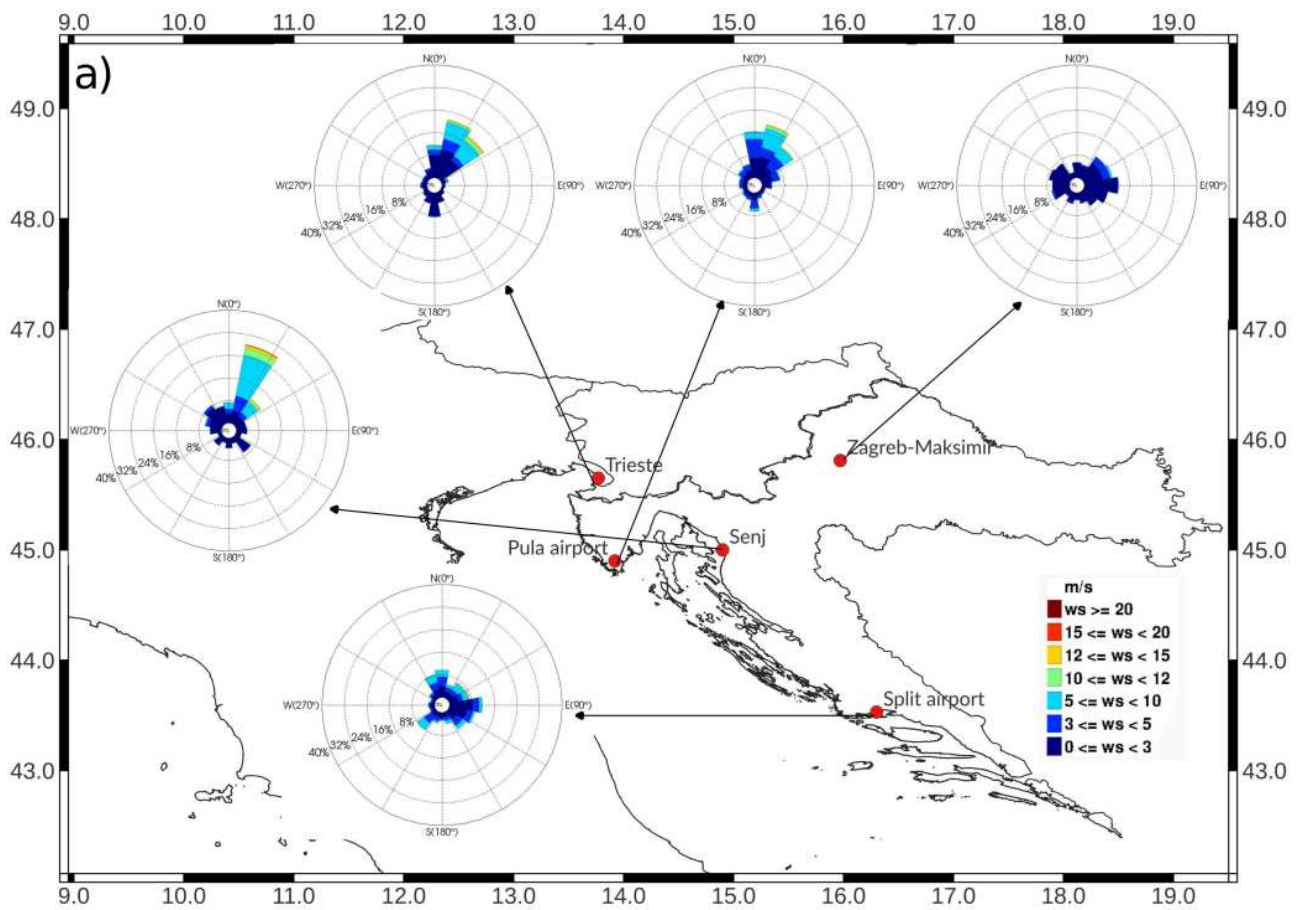
276 In previous sections, we showed that severe winds, which involve Bora and Sirocco along the Adriatic, can be simulated
277 with more details by CPMs. Here, we compare the simulated wind field to the actual observations. Since different
278 regimes generate wind flow in the coastal and the continental part of the Adriatic region, we do not expect CPMs to
279 have the same skill in simulating the wind field over the entire domain. Wind roses from observational stations (Fig.
280 4a), CPM ensemble mean (Fig. 4b) and the corresponding RCM ensemble mean (Fig. 4c) are shown for several stations
281 (Fig. 1b; Zagreb-Maksimir – inland station, Pula airport – coastal station in flat terrain, Trieste, Senj and Split airport –
282 three coastal stations in the complex terrain). The former two coastal stations are Bora representatives (e.g. Belušić &
283 Grisogono 2009, Telišman Kuzmić et al. 2013, Prtenjak et al. 2015), while the latter is a Sirocco representative (e.g.
284 Međugorac et al. 2015, Međugorac 2018).

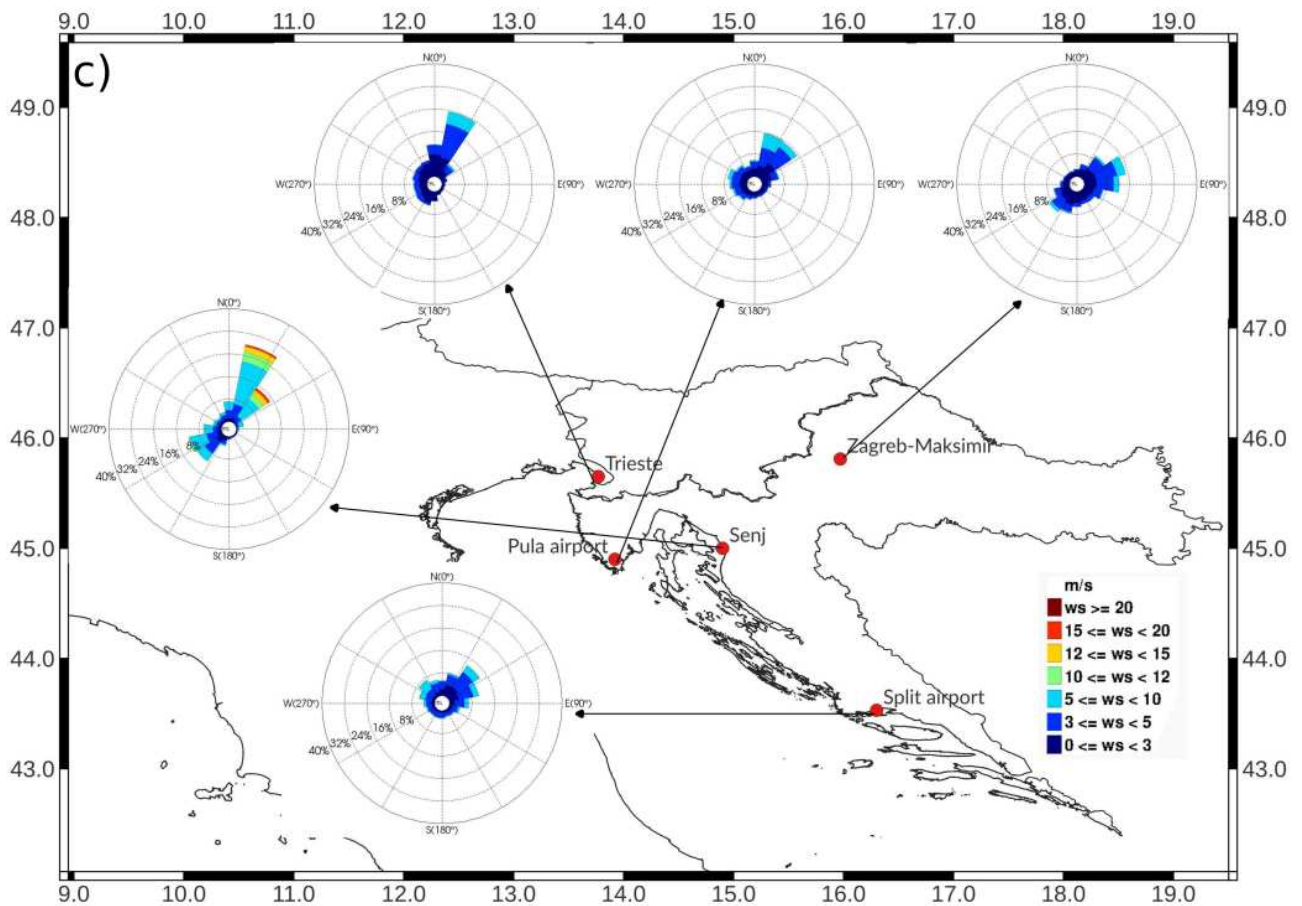
285 For the inland station (Zagreb-Maksimir), all wind directions are equally represented (~8% each) with the
286 maximum wind speed from 67.5° (NE direction) reaching 9.6 m/s. For the coastal flat part of the Adriatic region (Pula
287 airport) N-NE winds prevail contributing ~48% to the frequency distribution (where 25% is within the defined Bora
288 range). The maximum wind speed is 17 m/s blowing from 30°. Moving to the complex terrain, Bora occurs ~40% of the
289 time at both Trieste and Senj station in the northern Adriatic. The maximum 3-h wind speed at Trieste station is 20 m/s
290 blowing from 50°, while at Senj it is 19.2 m/s blowing from 22.5°. However, it is well-known that the observed wind
291 speed at Senj station should be considerably larger. This issue has previously been addressed by Bencetić Klaić et al.
292 (2009), who show that the location of the observational station is shielded from the Bora directions and therefore
293 underestimates the Bora wind speed. The wind speed observed at the station is underestimated by about 40%, but the
294 wind direction is realistic. Further south (Split airport), Sirocco becomes comparable to Bora in the number of observed
295 events, with Sirocco occurring 13% and Bora 14% of the time. The maximum wind speed still occurs for the Bora wind
296 and equals 23 m/s from 60°, while the maximum wind speed for Sirocco is 10 m/s.

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

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

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

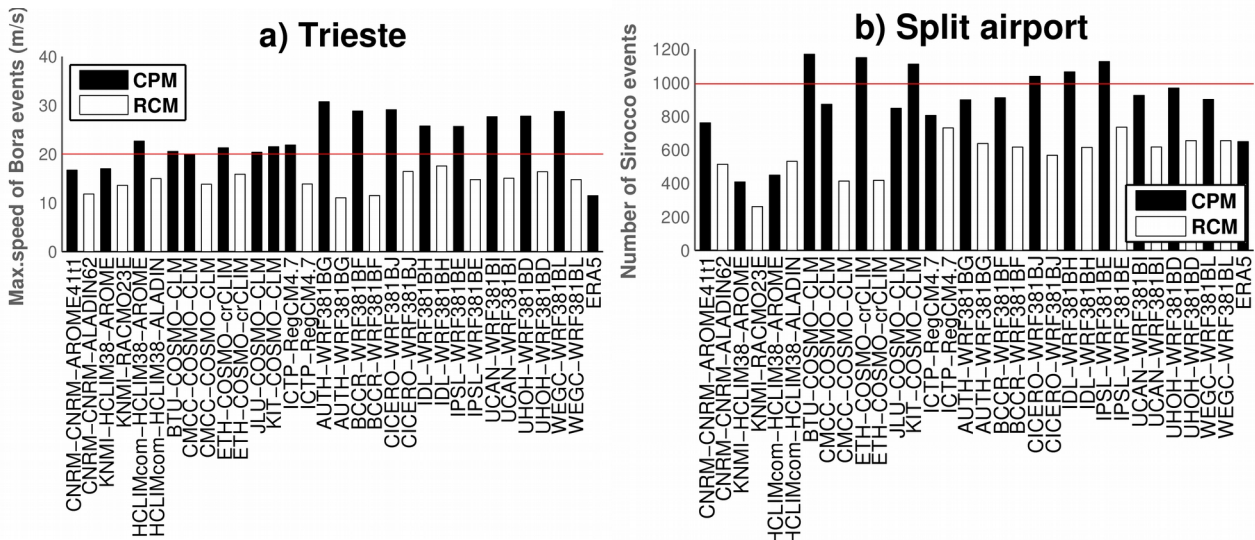




322 **Figure 4.** Wind roses for stations indicated in Figure 1b over the whole analyzed period. (a) observations (b) CPM
 323 ensemble mean, (c) RCM ensemble mean.

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

330 Sirocco frequencies, defined as strictly along shore in the southern Adriatic, are poorly simulated by RCMs,
 331 but CPMs approach close to observations. The underestimation of the number of Sirocco by RCMs (and ERA5) is
 332 larger (~50%), compared to Bora (20% shown in Fig. 4). Figure 5b supports the fact that CPMs strongly enhance the
 333 number of Sirocco events for all the simulations analyzed. The simulated frequencies come very close to the
 334 observations (~1000 events in DJF) except for CNRM-CNRM-AROME41t, KNMI-HCLIM38-AROME and
 335 HCLIMcom-HCLIM38-AROME. Those simulations would perform better for Sirocco angle definition starting at ~105°
 336 (7° discordance with our definition).



337 **Figure 5.** Cold season (DJF) Bora ($22.5^{\circ} - 68.5^{\circ}$) maximum wind speed at Trieste station (a) and Sirocco (112.5°
 338 -157.5°) frequencies at Split airport station (b) from all available simulations. Red line represents the observed values.

339 **3.5. THE SKILL IN BASIC STATISTICAL MEASURES**

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

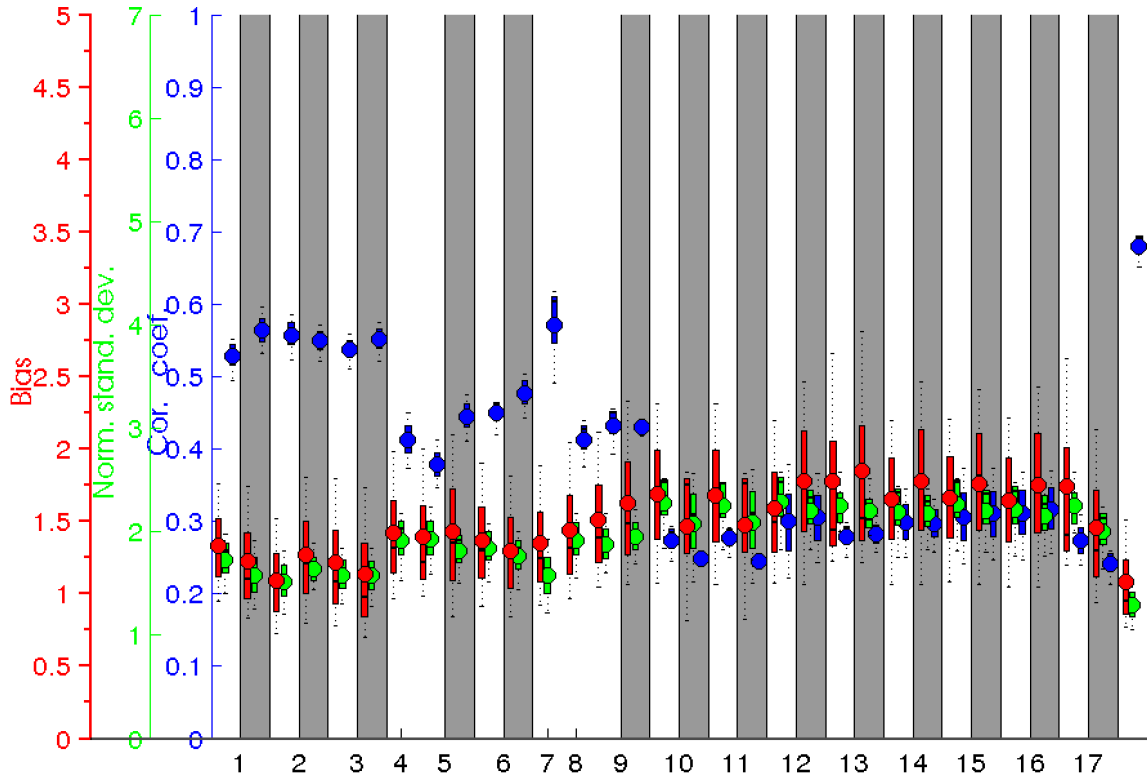
345 We can notice immediately that each CPM is strongly influenced by its parent RCM. If the RCM does not
 346 perform well, there are low chances that CPM will be excellent. It is important to note that this implies that here the
 347 choice of resolution affects the final results much less than the choice of particular CPM. This was also true for coarse
 348 (50 km) and fine (12 km) resolution RCMs in Belušić et al. (2018).

349 The difference between inland and coastal regions is in the larger spread among the stations for the latter for
 350 the particular statistical parameter. Grouping all the available stations for each terrain type (Fig. 6), the general picture is
 351 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),
 352 indicating a slight wind speed overestimation in the simulations, as we already indicated in section 3.3. Furthermore, the
 353 maximum biases in the coastal region with the complex terrain are two times larger than the other maximum biases,
 354 ranging from 1–4 m/s, indicating also a large spread of biases among stations. The simulated standard deviation for
 355 inland stations (Fig. 6a) usually follows the observed one very well, while in the complex terrain (Fig. 6b), where the
 356 wind intensity is high, the simulated standard deviation is up to 6 times larger than the observed one (depending on the
 357 simulation and station chosen). Summarizing, higher moments (i.e. standard deviation) of the distribution are worse
 358 simulated than central moments (i.e. mean) for both CPMs and RCMs. The presented comparison between inland and
 359 coastal station agrees with Obermann et al. (2016) and Belušić et al. (2018). However, the exact values should be
 360 interpreted with caution, since the in-situ observations are not necessarily entirely representative for the gridded climate
 361 output.

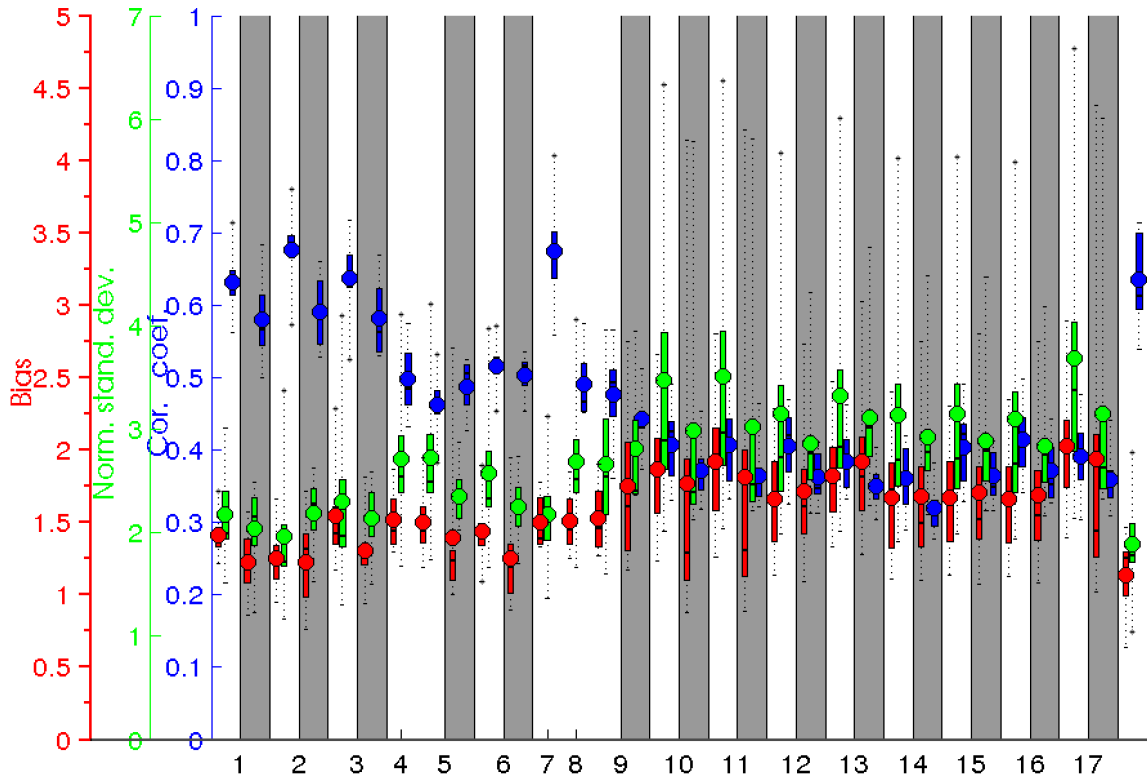
362 Even if climate simulations with CPMs and RCMs are not primarily designed to exactly follow the
 363 development of weather events, some members from the analyzed ensemble manage to follow the observed time series
 364 very accurately regardless of the internal variability inside the domain (CNRM-CNRM-AROME41t1,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

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

a) Inland stations (5)



b) Coastal stations (11)



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

379 4. SUMMARY AND CONCLUSIONS

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

- 387 • *The enhanced spatial variability.*
388 CPMs display fine spatial variability that is absent in coarser RCMs or reanalysis, leading to a larger spread in
389 intensities, which allows for capturing more extreme events. Much finer wind structures account for more
390 variable wind intensity and direction. They are especially evident over the entire mountainous ranges along the
391 coastline and in the vicinity of the isolated mountains in the lowlands. This is highly important for the realistic
392 simulation of severe wind formations such as Bora jets.
- 393 • *The possibility of simulating more intense wind speeds.*
394 Severe wind events are mostly associated with the Bora wind in the cold season. Therefore, potential added
395 value is higher in cold season compared to warm season due to the proportion of severe wind events. The
396 results have shown that severe winds are more frequent and could be much more realistically simulated in
397 high-resolution dataset. It is important to note that intense wind events show much larger sensitivity to changes
398 in resolution than low and moderate wind speeds.
- 399 • *Having enough skill to replicate the observed wind roses over the complex terrain and the ability of simulating
400 local winds realistically.*
401 Both CPMs and RCMs perform quite well in the flat terrain. In regions with complex topography, the
402 orographic forcing emphasizes the added value of CPMs: RCMs lose the skill in simulating both the wind
403 speed and direction distribution, while CPMs keep the reliable results. The main benefit of using CPMs is
404 detected for Bora maximum wind speeds in the northern Adriatic and for Sirocco frequencies in the southern
405 Adriatic. This discloses directly the link between better resolved topography and the representation of the
406 wind.
- 407 • *The skill in producing temporal correlation coefficient as high as in ERA5 reanalysis.*
408 Even if climate simulations with CPMs and RCMs are not primarily designed to exactly follow the
409 development of weather events, the assessment of the correlation coefficient showed that some of them
410 manage to fit accurately with the observed time series. We noticed that the choice of resolution (CPM or RCM)
411 affects the final results much less than the choice of the particular CPM. Simulations that showed superior skill
412 in terms of standard statistical scores in time are CNRM-CNRM-AROME41t1, KNMI-HCLIM38-AROME
413 and HCLIMcom-HCLIM38-AROME.

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588 **Competing Interests**

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

590 **Author Contributions**

591 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.

594 **Data availability**

595 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.