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Wind storminess in the Adriatic Sea in a climate change scenario

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In this work we assess the quality of the wind fields provided over the Adriatic Sea by the Regional Climate Model COSMO-CLM with reference to a control (CTR) period from 1971 to 2000 and to a future period from 2071 to 2100 under IPCC RCP 8.5 scenario (SCE), focusing on the implications for wave climate characterisation. Model skills have been assessed by comparing CTR results in terms of gross statistical properties and storm features against wind data from coastal observatories along the whole Italian Adriatic coast, showing a satisfactory capability of capturing the main features of mean observed seasonal variability. Significant achievements with reference to existing climatological models have been observed especially in terms of wind directionality, with unprecedented performances in reproducing the bimodal dominance of Bora (from northeast) and Sirocco (from southeast) in the northern basin, and the typical patterns of Bora jets flowing from the mountain ridges enclosing the Adriatic Sea on its eastern side. Future projections generally confirm the tendency to a decreasing energy trend envisaged by previous studies, with a more marked effect for extreme events in the northern basin.

Based on the comparison between climatological wind fields and the results of a SWAN wave model run forced by COSMO-CLM, we also define and test a criterion for a rapid identification of some relevant case studies for dedicated wave modelling experiments, without the need of running entire climatological wave simulations. This permits to focus the analysis of climatological oceanographic extreme events to a limited number of selected cases, allowing remarkable saving of computational effort especially if an ensemble approach is desired

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Key words: wind climate, climatological modelling, wave modelling inputs

INTRODUCTION

The increasing awareness of the hazards related to climate change impacts on coastal zones and the need for decadal to centennial adaptation or mitigation strategies (SLOTT *et al.*, 2006; TOL *et al.*, 2008; NICHOLLS, 2011) have been driving the development and implementation of several climatological modelling efforts at global to regional scale. This allowed to draw some estimates on possible change in different features of meteo-oceanic dynamics, such as temperature and precipitation patterns (GIORGI *et al.*, 2004), multi-annual fluctuations (VECCHI & WITTEMBERG, 2010), wave storminess and surge hazard (LIONELLO *et al.*, 2008; BENETAZZO *et al.*, 2012; CONTE *et al.*, 2014), as well as the effectiveness and implications of downscaling techniques (BELLAFIORE *et al.*, 2012). Together with sea level rise estimates, the identification of some evolution trends in the drivers of coastal morphodynamics, such as wind and wave climate, is highly desirable. Although necessary for providing a sound framework for the development of different long-term numerical modelling approaches for coastal processes prediction and management (CHINI & STANSBY, 2012; VAN MAANEN *et al.*, 2015; BONALDO *et al.*, 2015), this is still a relatively underrated activity. An appropriate evaluation of the meteo-marine climate is also crucial for predicting possible impacts on the mechanisms triggering large-scale circulation and deep sea ventilation, such as open sea convection (KILLWORTH, 1983; BENSI *et al.,* 2013) and dense water formation on continental shelves and downflow across the continental margin (IVANOV *et al.,* 2004; CANALS *et al.*, 2006; BENETAZZO *et al.*, 2014). These processes, although relevant for circulation at the mesoscale and above, can depend on meteo-oceanic processes characterised by strong intensity and sharp spatial gradients (VILIBIĆ & SUPIĆ, 2005; MIHANOVIĆ *et al.*, 2013; RICCHI *et al.*, 2016) and be strongly controlled by small-scale topographic features such as orographic gaps, therefore requiring a high spatial resolution in order to be completely described (SIGNELL *et al.*, 2005).

Although some experiments towards an ocean-atmosphere coupled approach in climatological studies have been set up (e.g. the EBU-POM regional climate model proposed by DJURDJEVIĆ & RAJKOVIĆ, 2010), a full coupling among wave, ocean and atmosphere dynamics (e.g. ZAMBON *et al.*, 2014; CARNIEL *et al.*, 2016) is presently unusual over this time scale in high-resolution models. Often representing the first stage of the climatological analysis, model datasets providing atmospheric information are generally sufficiently easy to source. In turn, the evaluation of climatologies for sea state descriptors from numerical wave models generally requires a further step with multi-decadal runs at a high computational cost, especially when an ensemble modelling strategy is desired. Moreover, this cost can be barely justified when the analysis is focused on the description of extreme events, which in fact are the reference in coastal risk management issues and in the development of protection and mitigation strategies. A possible alternative strategy consists of relying on regional downscaling of atmospheric modelling systems to identify sets of relevant events for the description of a given meteo-oceanic process. Once identified, these events can be further investigated via dedicated simulations with the possibility of increasing the resolution and the degree of complexity of the model framework, potentially adopting an ensemble approach.

In this direction, the present study explores the potential of the high-resolution implementation of the Regional Climate Model (RCM) COSMO-CLM (ROCKEL *et al.*, 2008), over the Adriatic Sea (BUCCHIGNANI *et al.*, 2016). This domain is an epicontinental system located in the northeastern Mediterranean basin and encompassed by the Apennines to the West, by the Alps to the North and by the Dinarides to the East. The Adriatic Sea is is a valuable test site for a broad range of meteo-oceanic applications, due to the peculiar processes taking place there and largely controlled by wind dynamics, such as dense water formation (SUPIĆ & ORLIĆ, 1999; VILIBIĆ & SUPIĆ, 2005; BENETAZZO *et al*, 2014) and the occurrence and possible co-existence of swell and generative sea states. In particular, swell seas are mostly dominated by Sirocco, a warm and humid southeasterly wind, while energetic generative seas are controlled by Bora, a cold and gusty northeasterly wind blowing in jets from orographic gaps (CAVALERI *et al.,* 1989; ORLIĆ *et al.*, 1994; KUZMIĆ *et al.*, 2013). Furthermore, the combination of morphological setting and strong anthropic pressure along the coasts, especially in the northern and central basins (TORRESAN *et al.*, 2012; ACCIARRI *et al.*, 2016), together with a long-standing coastal sediment deficit (NELSON, 1970), bestow paramount importance to the issue of long-term coastal planning and protection in this area. This work aims at:

1) Assessing the reliability, and improvements with respect to previous state of the art, of the wind estimates provided by the RCM COSMO-CLM at high-resolution, with a focus on the peculiar characteristics of the Adriatic Sea;
2) Identifying the main features of the present wind climate over the Adriatic Sea and expected modifications in a climate change scenario of utmost severity, with special care to the highly energetic events and their possible implications in terms of kinetic energy injection into the ocean surface layers and wave generation;
3) Assessing the possibility of using high-resolution COSMO-CLM model results as a proxy for the identification of severe wave storm that may strongly impact the Adriatic coasts.

MATERIALS AND METHODS

Climatological projections of atmospheric variables have been obtained with the RCM COSMO-CLM (ROCKEL *et al.*, 2008). This is the climate version of the operational non-hydrostatic mesoscale weather forecast model COSMO-LM (STEPPELER *et al.*, 2003), developed by the German Weather Service (DWD). Likewise its operational counterpart, COSMO-CLM solves the non-hydrostatic formulation of the Navier-Stokes equations for a compressible flow assuming a hydrostatic base state at rest. The atmosphere is treated as a multicomponent fluid (dry air, water vapour, liquid and solid water) for which the perfect gas equation holds and it is subjected to the gravity and the Coriolis forces. The unresolved subgrid-scale phenomena are taken into account in a statistical manner through a number of parameterizations. While COSMO-LM is driven by operational global weather forecast models, COSMO-CLM forcings are provided by the Global Climate Model CMCC-CM (SCOCCIMARRO *et al.*, 2011). COSMO-CLM has been validated within several projects such as PRUDENCE (CHRISTENSEN *et al.*, 2007), and its response has been found to be in the same range of accuracy as other RCMs, resolving similar scales. The RCM COSMO-CLM was used to perform a climate simulation over Italy, employing a spatial resolution of about 8 km, over the period 1971-2100 according with the IPCC RCP8.5 scenario (MOSS *et al.*, 2010), predicting a generalized warming and a predominant reduction in precipitation, especially in summer (BUCCHIGNANI *et al.*, 2016; ZOLLO *et al.*, 2016).

Initial and boundary conditions were provided by the coupled atmosphere-ocean general circulation model CMCC-CM (SCOCCIMARRO *et al.*, 2011). In this work, datasetes referred to two different periods have been extracted for the analysis, namely under Control (CTR, 1971-2000) and climate change Scenario (SCE, 2071-2100) conditions.

Climatological wind fields from COSMO-CLM simulations were used as a forcing for two 30-years runs carried out within the phase-averaged wave model SWAN (Simulating WAves Nearshore, BOOIJ *et al.*, 1999) for describing spectral properties of sea states in the Adriatic basin. Model grid horizontal resolution ranges from approximately 7 km along the central and easternmost reaches of the Adriatic Sea down to 2 km along the Italian coasts (Fig. 1). The bathymetry results from a merging of high-resolution multibeam data collected during several oceanographic surveys in the northern basin and along the Southern Adriatic margin (FOGLINI *et al.*, 2016; BONALDO *et al.,* 2016), interpolated on the domain grid. Sea level rise in the climate change scenario was taken into account by increasing the water depth by 0.70 m based on estimates provided by ANTONIOLI *et al.* (2017). Following the established implementation by BENETAZZO *et al.* (2013 for a thorough validation; see also BENETAZZO *et al.*, 2014 for another application), the wave fields were represented by components propagating in 36 evenly spaced directions and discretised into frequencies geometrically distributed between 0.05 and 0.5 Hz, with 360 s time step. Calm conditions were prescribed in the initialization of each run and wave radiation was allowed out of the southern boundary, while no waves were allowed to enter the domain.

Wind data from coastal observatories

Wind data relative to present conditions for CTR run evaluation were retrieved from the *Rete Mareografica Nazionale* (http://www.mareografico.it/), a national network collecting tide, waves and wind data along the Italian coasts. Most of the data sets span the 2010-2015 period (Table 1), covering an integer number of years in order to preserve the significance of annual statistics.

Although such a relatively short period may not be fully sufficient for drawing thorough climatological inferences, the spatial coverage encompassing the whole Italian Adriatic coast allows to assess geographical variability in model skills.

Model results post-processing

With reference to both CTR and SCE datasets, we considered the zonal and meridional components of the wind velocity at 10 m height, referred to local values at the coastal observatories and spatially averaged over the Northern Adriatic (NA, north of the Ancona-Novalja transect, see CARNIEL *et al.*, 2016; Fig. 1) and Southern Adriatic (SA) basins, and on the whole Adriatic (WA) Sea. For each subdomain we considered the specific kinetic energy of the wind (e_k) in the lower layers of the atmosphere potentially available for wave generation (USACE, 2002). This quantity was used instead of the significant wave height H_s to characterise *a priori* (namely, without relying on wave model results) the storm events, following the procedure suggested by

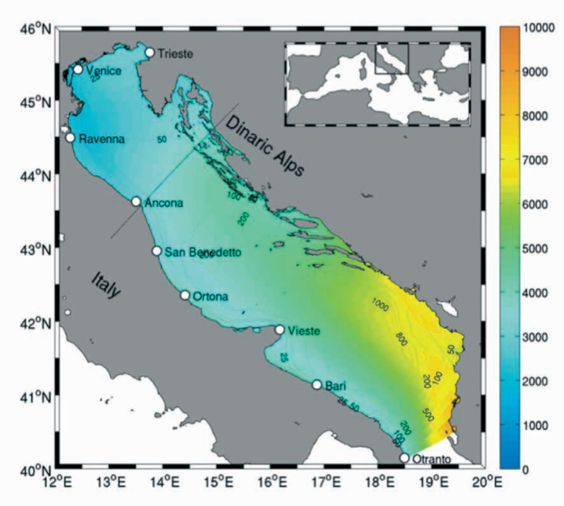

Fig. 1. Adriatic Sea and its position in the Mediterranean region. Contours outline basin bathymetry, white dots indicate the position of the measurement stations and the colour scale represents the horizontal resolution of the wave model grid. The thin dotted line indicates the Ancona-Novalja transect, here taken as a conventional boundary between the Northern and Southern Adriatic basins

Table 1. Measurement stations along the Italian Adriatic coast

Name	Coordinates (Lon-Lat)	Period
TRIESTE	13°45’28.58” - 45°38’57.81”	01/01/2010 – 31/12/2015
VENICE	12°25’35.50” - 45°25’05.59”	01/01/2010 – 31/12/2015
RAVENNA	12°16’58.57” - 44°29’31.47”	01/01/2010 – 31/12/2015
ANCONA	13°30’23.46” - 43°37’29.16”	01/01/2010 – 31/12/2014
SAN BENEDETTO	13°53’23.13” - 42°57’18.44”	18/06/2010 – 18/06/2016
ORTONA	14°24’53.50” - 42°21’21.24”	01/01/2010 – 31/12/2015
VIESTE	16°10’37.24” - 41°53’17.10”	01/01/2010 – 31/12/2015
BARI	16°51’57.72” - 41°08’24.74”	01/01/2010 – 31/12/2014
OTRANTO	18°29’49.52” - 40°08’49.74”	01/01/2010 – 31/12/2015

BOCCOTTI (2000). This approach prescribes the identification of the events in which e_k exceeds a threshold (prescribed as 1.5 times its time-averaged value), the aggregation of events parted by less than 10 hours for ensuring stochastic independency, and the removal of the events lasting less than 12 hours. Each storm was thus characterised in terms of duration and a Kinetic Energy Index (KEI) computed by integrating over time the wind power per unit mass and area during the event, namely:

$$KEI = 0.5 \int_{t_1}^{t_2} UV^3 dt$$

where UV is the wind speed and t_1 and t_2 represent the start and the end of a storm. The KEI provides an indication of the overall wind energy acting at a given location during a storm, and it has been used in the computation of the return period (namely, the inverse of the probability that an event with given intensity is equaled or exceeded in one year) of each event.

For each considered measurement site and based on the whole time series, we calculated observed and modelled monthly climatological averages and standard deviations of the wind specific kinetic energy, discriminating among four quadrants of wind origin. This allowed an evaluation of the model performances and a bulk assessment of the wind energy trend. Spatial patterns of the statistics of modelled quantities have been explored by computing, on each grid point, both the relevant percentiles of the wind speed considered within the whole time series, and the values corresponding to different return periods of the storm events. By averaging the information over the different subdomains and considering different months, climatological information about the the seasonal variability of the frequency and intensity of the modelled events were extracted. In order to explore the representativeness of the identification of potential storms based on the wind speed, we applied again the method proposed by Boccotti to the spatially-averaged significant wave heights retrieved from the SWAN runs. For each event an overall Wave storm Energy Index was computed as

$$WEI = \int_{t_1}^{t_2} H_s^2 T_{m-10} dt$$

where $T_{m\text{-}10}$ represents the spectral energy period, H_s is the significant wave height. Then we compared the return period of any wave storm with the return period of its generating wind event, if classified as a storm.

RESULTS AND DISCUSSION

CTR run validation

With respect to wind energy, model results exhibit a generally fair capability of reproducing mean values and variability (Fig. 2), together with the seasonal fluctuations of these quantities (Fig. 3), although with an overestimation in the monthly average and in the seasonal variability. In this, it is also worth noting that some information on the instruments installation is not fully complete, allowing some uncertainty on the evaluation of the retrieved data. The agreement of the directional variability and the identification of dominant winds is significantly enhanced compared to data sets resulting from previous numerical experiments (see BELLAFIORE *et al.*, 2012), although some shortcomings still arise in the presence of complex geometries and immediately downstream of orographic features. This is for instance the case of the Trieste station, where the model representation of the coastal mountain ridge morphology can locally jeopard-

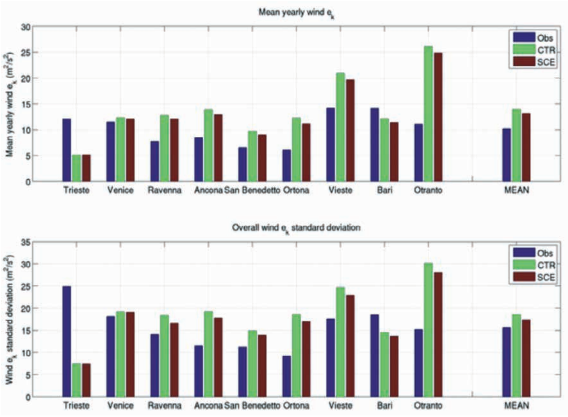

Fig. 2. Overview of observed and modelled mean (top) and standard deviation (bottom) wind specific kinetic energy at the measurement stations.

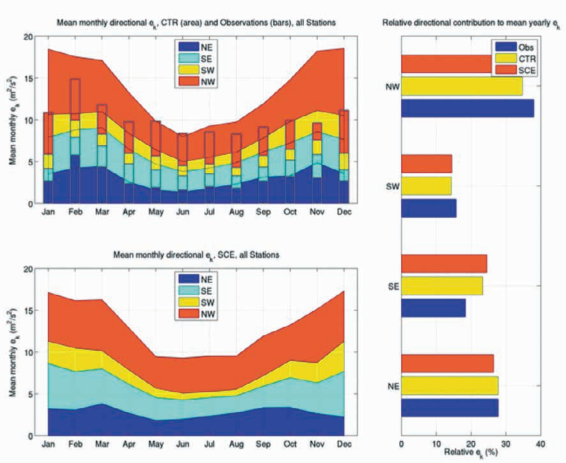

Fig. 3. Mean monthly wind specific kinetic energy in observed data (top left, bars), CTR (top left, area) andSCE (bottom left). The relative directional contribution is graphically depicted by the coloured areas and summarised over a yearly basis in the bar graph on the right-hand panel.

ize the description of patterns and intensity Bora jets intrusion from the orographic gaps (CARNIEL *et al.*, 2009; HORVATH *et al.*, 2011; CARNIEL *et al.*, 2016). On the other hand, the dominance of Bora and Sirocco in the NA is clearly established downstream at Venice station. The capability of reproducing realistic spatial patterns of wind is exemplified by considering two instantaneous wind fields referred to different intense events depicted in Fig. 4. The left panel, referred to a typical Bora condition, shows (up to our knowledge, for the first time at this degree of definition in a climatological model) the well-known multiple jet system from the Dinarides (see KUZMIĆ *et al.*, 2013; RICCHI *et al.*, 2016). The right panel shows the configuration known as "dark Bora" (PASARIĆ *et al.*, 2009), dominated by Sirocco eventually and rotating in the northern basin, giving rise to strong, humid northeasterly winds along the Italian coasts.

Overall, mean wind specific kinetic energy e_k in the CTR run exceeds by approximately 36% the values from the observed time series, this overestimation being mostly concentrated in the central and southern Adriatic basin stations and in winter months (October to March). Although still presenting room for desirable improvements, it is worth noting that this performance represents a significant improvement compared to previous recent results (BELLAFIORE *et al.*, 2012).

Fairly satisfactory performances are obtained in terms of storminess characterisation (Table 2) in which, although with a 15% underestimate of the occurrence frequency by the model, the directional distribution of the storms is generally well captured.

Wind climate projections in the Adriatic Sea

Accordingly with estimates from previous studies (LIONELLO *et al.*, 2008; BENETAZZO *et al.*,

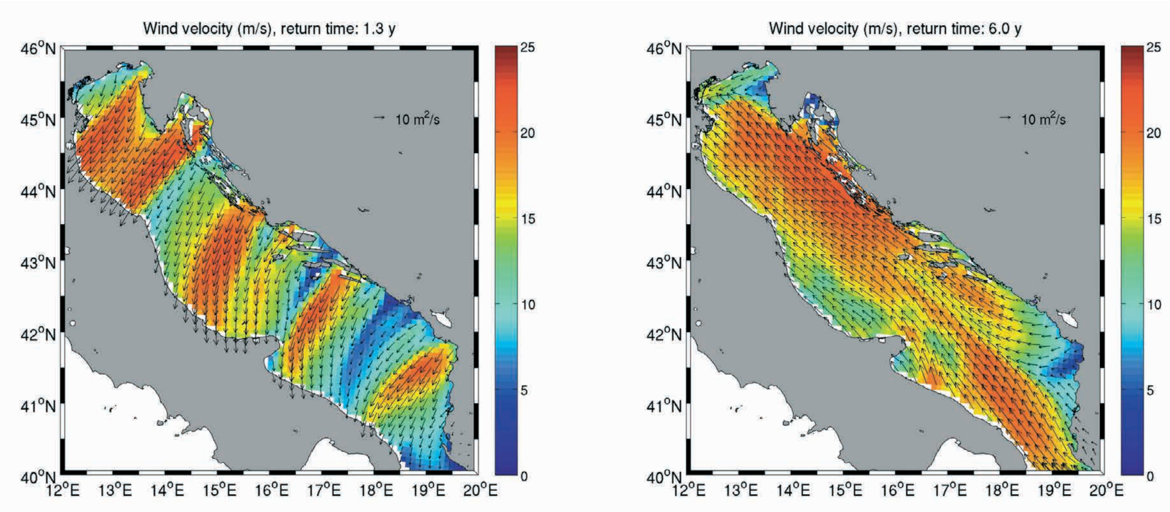

Fig. 4. Extreme events showing some typical wind patterns of the Adriatic Sea, namely Bora jets (left panel) and Sirocco (right). In the latter case it is worth noting the rotation of the wind field in the north, giving rise to the configuration known as "dark Bora"

Table 2. Observed and modelled wind storms at the measurements sites, mean yearly occurrence and percent directional distribution. Storms were identified as the events in which the specific kinetic energy exceeds 1.5 times its time-averaged value for a given location,aggregating events parted by less than 10 hours and removing the events shorter than 12 hours

		OVERALL			**EXTREME**		
		Detection %	p	S	Detection %	p	S
NA	*Bora*	75	2.27	1.21	83	2.26	7.47
	Sirocco	58	0.18	0.22	67	0.16	0.68
	All	66	0.85	1.10	73	0.83	6.63
SA	*Bora*	74	2.26	0.30	67	2.36	2.53
	Sirocco	86	0.62	1.37	94	0.61	6.86
	All	78	0.47	1.04	90	0.46	6.34
WA	*Bora*	72	2.57	0.42	75	2.84	4.06
	Sirocco	84	0.36	1.59	94	0.35	7.55
	All	76	0.38	1.32	90	0.36	6.59

2012), climatological projections tend to suggest a tendency towards an overall wind energy decrease in the lowermost levels of the atmosphere at the observation sites (Fig. 3). In fact, considering the broader picture of the whole Adriatic basin and its mainland, a more heterogeneous scenario arises in the expected variations of the energetic conditions. Fig. 5 shows that wind speed associated to moderate (75 percentile) to severe (99 percentile) conditions is actually expected to undergo a 0-10% decrease across the whole Adriatic Sea, although mostly with stronger decrease along the Bora jets patterns. On the other hand, in the mainland the variability is stronger, allowing the possibility of local increases especially nearby mountain ridges and in downstream regions. Considering the overall energy developed during a storm, Fig. 6 shows that in the Northern Adriatic the value of KEI is expected to decrease by 5% its control value for return periods up to one year and more than 10% for return periods

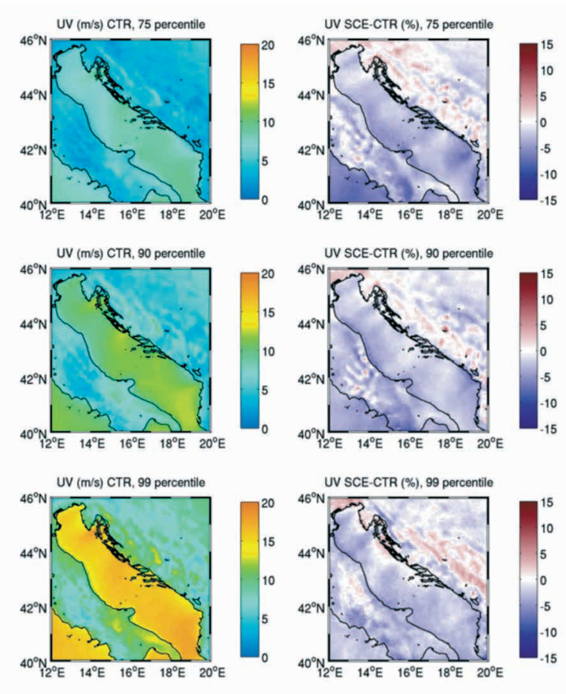

Fig. 5. Patterns of modelled wind velocity corresponding to 75 (top), 90 (middle) and 99 (bottom) percentiles in the CTR run (left) and percent variation in the RCP8.5 scenario (right)

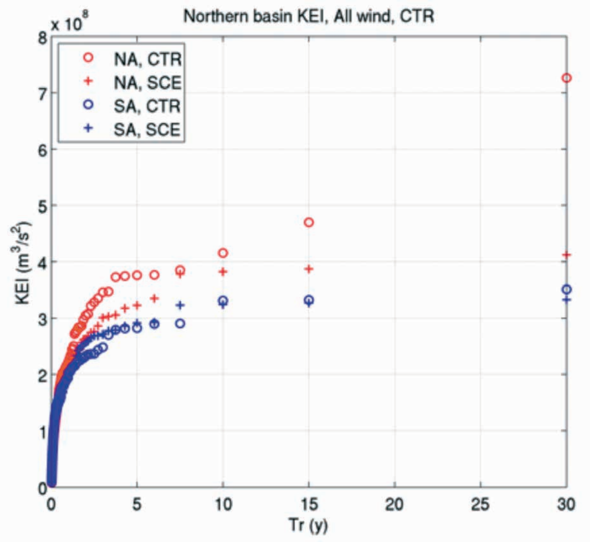

Fig. 6. Space-averaged Kinetic Energy Index associated wind storms with different return periods in CTR and SCE conditions

above 5 years. In the southern basin the intensity of storms with return period greater than one year is generally smaller, and expected variations are very small as well, with the possibility of small increases between 1 and 10 years return period. The average number of storm episodes in the Northern Adriatic Sea in the CTR run is 39.5 events per year, almost invariant in SCE, associated with a -8.2% decrease in the cumulative yearly value of KEI in the climate change scenario. In the face of this slight change in terms of overall energy amount potentially available for the generation of wave storms, model runs suggest a more significant modification in the directional distribution of wind episodes towards an adjustment of the relative energy contribution of Bora and Sirocco. In fact, cumulative yearly KEI associated with Bora episodes undergoes a -29.3% decline, whereas the value of this parameter associated with Sirocco storms exhibits a +22.2% increase. In the Southern Adriatic Sea, the number of storms is expected to remain nearly unchanged (from 46.3 to 46.6 events per year) with a -4.5% decrease in terms of cumulative yearly KEI. Here, the energetic contribution of Bora storms is not as strong as in the northern basin, whereas Sirocco provides nearly 46% of the whole storm energy both in the CTR and in the SCE runs. Worth pointing out, while the indications of Bora and Sirocco KEI trends in the Northern Adriatic Sea are supported by a 95% significance test, the estimates on storminess and KEI in the Southern basin should only be considered as orientative.

Extreme wave storms identification from wind model data

In the Fig. 7 authors provide an overview of the applicability of the wind KEI as a proxy for the identification of relevant events for oceanographic climatological simulations, based on both runs aggregated Table 3 summarizes the main statistical parameters of this relation for the different domains, providing the detection rate, the slope of best fit lines and the root mean square deviation of the distributions. Concerning the northern basin, wave events that were actually predicted by the Kinetic Energy parameter (66% overall, and 73% of the events with return period equal or greater than 1 year) are clustered along two main trends. The return period of Sirocco-induced wave storms intensity is generally underestimated by the Kinetic Energy parameter. This, together with the relatively low detection rate (58% in the whole dataset, 67% among the extreme events) is due to the fact that the features of swell sea states in the northern basin are the result of the action of Sirocco along the main axis of the basin, which is not always

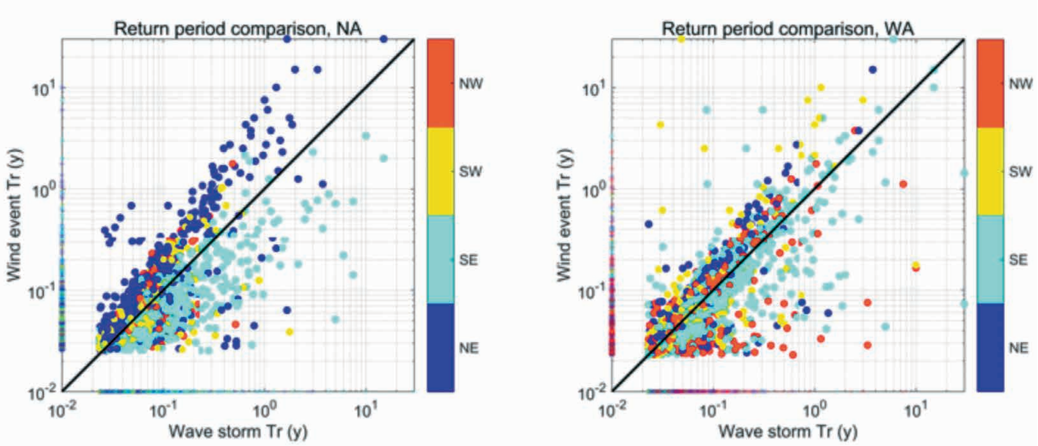

Fig. 7. Return period of wind events associated to wave storms in the Northern (left) and Whole (right) Adriatic Sea. For every wave storm event with a given return period along the x-axis, the corresponding value along the y-axis identifies the return period of the wind event responsible for that wave storm episode, and the colour represents the direction of the wind source. Points spread along the x- and y- axes represent respectively the wave events whose generating wind conditions were not identified as storms, and wind events locally characterised as storms that did not give rise to a wave storm

Table 3. Representativeness of the wind KEI proxy for the identification of storm events in different conditions. p and S are respectively the slope of the best fit lines of the wind and wave return periods and the associated root mean square deviation

		Storms per year	**% NE**	**% SE**	**% SW**	**% NW**
Trieste	Obs	35.86	86.38	11.27	0.00	2.35
	CTR	33.67	66.63	22.57	10.59	0.20
Venice	Obs	39.84	71.97	14.23	10.04	3.77
	CTR	33.40	64.17	18.56	10.78	6.49
Ravenna	Obs	42.18	35.97	42.69	5.14	16.21
	CTR	33.40	47.41	23.05	16.67	12.87
Ancona	Obs	52.21	13.79	13.41	21.84	50.57
	CTR	36.13	34.13	14.21	17.71	33.95
San Benedetto	Obs	38.31	40.00	6.52	2.61	50.00
	CTR	33.80	23.96	11.44	7.00	57.59
Ortona	Obs	41.84	15.94	4.38	34.66	45.02
	CTR	35.90	9.10	13.09	9.75	68.06
Vieste	Obs	48.18	6.92	14.53	9.34	69.20
	CTR	42.60	6.57	25.04	7.82	60.56
Bari	Obs	46.21	3.03	19.48	6.93	70.56
	CTR	36.57	6.84	22.88	11.49	58.80
Otranto	Obs	44.51	11.61	10.86	8.99	67.42
	CTR	45.50	7.84	46.52	6.74	38.90

fully described by local wind conditions. Indeed, the detection rate for Sirocco increases significantly when considering the whole basin in the analysis (84% overall, 94% for extreme events), although with some underestimation. Bora detection rate, in turn, is more satisfactory in the north (75% overall, 83% among the extreme events), but in this case the sea state severity tends to be overestimated, presumably due to the fact that the sea state development is fetch-limited. In the southern basin, where the dominance of Bora and Sirocco is less important, this behaviour is not as much evident, but the detection rate and the fitting parameters are still on the same order of magnitude and variability.

CONCLUSIONS

Together with sea level rise, and in some cases even more effectively, wave climate modifications can be the main threat for coastal stability, especially in the case of moderate- to high-energy sandy coasts (MORTLOCK & GOODWIN, 2015). The capability of capturing wind climate variability over a decadal time scale is crucial for providing a realistic quantification of wave dynamics and coastal sediment transport processes (CARNIEL *et al.,* 2011; ALMAR *et al.*, 2015; BONALDO *et al.*, 2015), identifying possible erosional and depositional hotspots and setting intervention priorities for coastal management. This is particularly relevant in the case of semi-enclosed seas such as the Adriatic Sea or the Baltic Sea, in which waves, currents and sediment transport patterns are strongly controlled by the relationship between basin geometry and variations in wind intensity and direction (SCLAVO *et al.*, 2013; SOOMERE & VIŠKA, 2014; SOOMERE *et al.*, 2015). In this work we assessed modelled COSMO-CLM wind climate data over the Adriatic Sea at 8 km horizontal resolution under the high-emission IPCC RCP8.5 scenario. Furthermore, we explored the possibility and limitations of using wind model data for identifying storm events of particular relevance for coastal protection on which to concentrate wave modelling efforts, possibly with an ensemble approach. Due to the temporal span of the observational dataset considered in this study, the comparison with the model results should be considered as an overall evaluation of the model performances instead of a thorough climatological validation. In turn, benefiting from to the spatial coverage of the dataset, the results of this evaluation can be specified along the whole axis of the Adriatic Sea, to some extent compensating the limitations of the time series length.

With this *caveat* in mind, the results of this work allow to integrate meteo-oceanographic projections for the Adriatic Sea with some relevant practical implications. Besides providing a quite satisfactory description of climatological wind fields, COSMO-CLM exhibits a remarkable capability of replicating wind directionality and sharp spatial gradients. This skill is generally rather uncommon in climatological models, although particularly important for an appropriate description of processes dominated by kinetic energy and heat exchanges between atmosphere and ocean. For this reason, COSMO-CLM represents a wealthy potential for a broad set of climatological oceanographic applications, from dense water production and thermohaline circulation to the description of wave climate and the likely threats for coastal morphological stability. The decreasing trend of storminess in the Adriatic Sea predicted by several models in moderate to severe emission scenarios (BELLAFIORE *et al.*, 2012; BENETAZZO *et al.*, 2012) is here confirmed, on average, with reference to the IPCC RCP8.5 scenario. Although the decrease of yearly number of storm events is not generally statistically significant, the energetic trend seems more defined especially in the northern basin, consolidating the established relationship between global changes induced by intense carbon dioxide production and local climatological effects in this area.

In the case that the computational requirements are the limiting factor for oceanographic applications, our verification of the representativeness of wind KEI as a proxy for identifying potential storms allows to focus climatological evaluation on some extreme events, though with some caution to the definition of the spatial domain based on the events to be considered. The detection rate is generally satisfactory when the identification of events potentially leading to severe sea state for a given wind is performed on a basin in which this wind blows with reasonably uniform intensity. This is indeed the case of Bora in the northern Adriatic Sea and of Sirocco in the whole basin. On the other hand, although a general character of “extreme” intensity is captured for the most part, the return period of modelled wind events is generally not precisely representative of the sea state generated under those conditions. For this reason, a climatological study of extreme storms identified based on a metric of the wind kinetic energy should presently consider a suitable number of cases in order to properly compensate the uncertainties related with the use of this proxy.

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Utjecaj olujnog vjetra na Jadransko more u uvjetima klimatskih promjena

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SAŽETAK

U ovom radu ocjenjujemo kvalitetu polja vjetra nad Jadranskim morem dobivenog primjenom Regionalnog klimatskog modela COSMO-CLM za kontrolno razdoblje (CTR) od 1971. do 2000. i za buduće razdoblje od 2071. do 2100. uz pretpostavku klimatskog scenarija IPCC RCP 8.5 (SCE), s posebnim osvrtom na posljedice za valnu klimu.

Kvaliteta modela procijenjena je usporedbom njegovih rezultata za CTR-a s podacima vjetra s obalnih opservatorija duž cijelog talijanskog dijela jadranske obale na temelju ukupnih statističkih i olujnih svojstava. Usporedba je pokazala zadovoljavajuće rezultate modela pri reproduciranju glavnih obilježja srednje opažene sezonske varijabilnosti.

Značajna unapređenja u odnosu na postojeće klimatske modele dobivena su posebice u reproduciranju smjera vjetra, kao i pri uspješnoj reprodukciji bimodalne dominacije bure (sa sjeveroistoka) i juga (s jugoistoka) u sjevernom bazenu, te tipičnim obrascima bure s jakim intenzitetima ispred planinskih prijevoja duž istočne obale Jadranskoga mora.

Buduće projekcije općenito potvrđuju negativni trend energije predviđen i prethodnim studijama, s izrazitijim učinkom na ekstremne događaje u sjevernom bazenu.

Na temelju usporedbe klimatoloških valnih polja i rezultata valnog modela SWAN forsiranog izlaznim poljima COSMO-CLM modela, definirani i testirani su kriteriji za brzu identifikaciju relevantnih situacija u modeliranju valova bez potrebe za izvođenjem cijele klimatološke simulacije valova. To dozvoljava da se analiza klimatoloških oceanografskih ekstremnih događaja usredotoči na ograničeni broj odabranih slučajeva, čime se omogućava značajna ušteda računalnih resursa pogotovo ako se želi primjeniti ansambl modela.

Ključne riječi: klima vjetra, klimatološko modeliranje, ulazni podaci za modeliranje valova