On the assessment of RCMs in simulating deep cyclones over the Mediterranean region: Impacts on the storm surges of coastal areas

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Abstract: The Mediterranean region, especially its coastal sites, has been proven in the past to be highly sensitive to Climate Change impacts, experiencing water management problems due to coastal hazards such as inundation by storm surges and sea level rise, land loss, etc. The overarching goal of the present study, being a part of the MEDAQCLIM project, is to assess the ability of updated RCMs in simulating the main meteorological parameters, leading to storm surge-induced sea level variations over the domain of interest. Three climate models were selected and compared with the CERA re-analysis database focusing on the simulation of the mean SLP level, the mean wind fields and the reproduction of the extreme barometric systems (Deep Depressions) over the Mediterranean region. Through thorough validation of the RCM outputs it is concluded that, in general, all models present a relatively high simulation skill in representing the main characteristics and spatial distribution of the examined parameters, with some differences depending on the time scale the examination takes place. Indicative evaluation of maritime hydrodynamic model hindcasts is also provided based on comparisons of storm surge simulation outputs against field observations of coastal hydrographic features.

1 Introduction

Recent projections by both general circulation models (GCMs) and regional climate models (RCMs) show that future climate will be characterized by monthly net rainfall decrease during winter and potential evapotranspiration increase during summer due to global warming. These climatic alterations will vary from one region to another, but many densely populated countries would be seriously affected. All expected Climate Change (CC) scenarios, as defined by Intergovernmental Panel for Climate Change (IPCC) 5th Assessment Report (AR5), will induce a permanent stress on surface and coastal waters. Specifically, intense storm surge events are estimated to threaten low-land coastal areas by inducing severe inundation hazards. In the past, storm surges have been responsible for human casualties, loss of land and property, damages to onshore infrastructure, harbor structures and coastal defenses. CC has been associated with such impacts on the coastal zone at regional scales (Androulidakis et al., 2015; Makris et al., 2016), *i.e.* influencing the intensity and frequency of occurrence of extreme storm surges (Makris et al., 2016; Galiatsatou et al., 2019). It is also expected that the Mediterranean region will be among the areas that will be most affected by CC (Cramer et al., 2018). CC and climate variability can increase the risks and costs of integrated coastal zone management, lead to quantitative and qualitative degradation of coastal water resources, and subsequently influence socio-economic vulnerability and environmental sustainability of coastal zones.

2 Data and Methodology

Data from three RCM implementations driven by output of GCM simulations are used, in order to evaluate their skill in simulating both Sea Level Pressure (SLP) and Wind fields over the domain of the Mediterranean region. The aforementioned data were downloaded from the MED-CORDEX database (www.medcordex.eu) covering a 30-year period from 1971 up to 2000 (reference period). More specifically, the selected RCMs are: **CMCC-CCLM4-8-19 v.1**, **CNRM-ALADIN52 v.1** and **GUF-CCLM-NEMO4-8-18 v.1** (Ruti et al., 2016). All three RCMs were compared with one of the most updated reanalysis data base (**CERA,** https://www.ecmwf.int/en/research/projects/cera) (Laloyaux et al., 2018). Even though the whole analysis took place on an annual, period (cold – warm), seasonal and monthly scale, the results presented here only refer to the annual ones, due to space limitations. Apart from the mean SLP fields an attempt was made to assess the skill of the examined models in simulating the deep depressions over the Mediterranean region. In order to detect the deep cyclones (depressions with center pressure lower to 1000 hPa; Trigo et al., 2002), the methodology introduced by Rousi (2014) was applied. The proposed algorithm uses gridded data of daily SLP primarily for CERA and secondarily for the RCMs, accounting for the time period 1971-2000. Maps illustrating the frequency of occurrence of deep depressions (days) were also computed. Thus, the ability of the models to simulate both the regions where these deep depressions are found as well as their frequencies can be assessed. It is highlighted that in order for a day in a specific grid point to be characterized as a “day of deep depression” two criteria had to be fulfilled. First, on that day, SLP in the grid point must be lower than 1000 hPa. The following necessary condition is for neighboring grid points to have higher pressure values than the examined one, in order to identify it as the center of cyclogenesis with an increasing pressure gradient from the center and outwards. The related surge-induced sea surface height (SSH) in coastal areas was numerically simulated with a 2-DH barotropic model of depth-averaged shallow water equations for hydrodynamic circulation, called MeCSS (Androulidakis et al., 2015; Makris et al., 2016).

3 Results

3.1 Sea Level Pressure analysis

Regarding the mean annual, derived from re-analysis CERA data, it is found that the pressure values range from 1013 up to 1020 hPa with an increasing gradient from east to west-northwest. The minimum is located over Cyprus and the highest ones at the north in the Iberian Peninsula (Fig. 1). The comparison of the equivalent spatial distribution of SLP values, simulated by the CMCC, CNRM and GUF models, showed that all RCMs are able to capture the main characteristics of this field on an annual basis with the lowest values at the most eastern part of the Mediterranean Sea and the highest over to the west. The calculated differences, which were evaluated applying the t-test at a level of significance 0.05, revealed that CMCC tends to slightly overestimate the actual SLP values all over the domain of study. Small positive differences cover almost the entire Mediterranean region (up to 3hPa) and only at a limited area at the northwest the computed differences are negative. However, even though the magnitude of the differences is small, most of the grid points were found to be statistically significant since the applied test takes under consideration not only the actual compared values of the time series, but also the discrepancies in their variability. Regarding CNRM, the difference pattern divides the Mediterranean region in half; a) the northern continental parts are characterized by negative differences (underestimated SLP values); b) the marine part (as well as southeastern Med) where positive differences are found. Values vary from -3 hPa to 3.5 hPa. The GUF model overestimates the annual surface atmospheric circulation at the south and the Iberian Peninsula (positive differences), while in the northern part of the domain the differences are negative (underestimation of SLP values). As in the aforementioned RCMs, also for this one, the actual differences values are small showing that the models present a quite efficient skill in simulating the main SLP characteristics during the year.

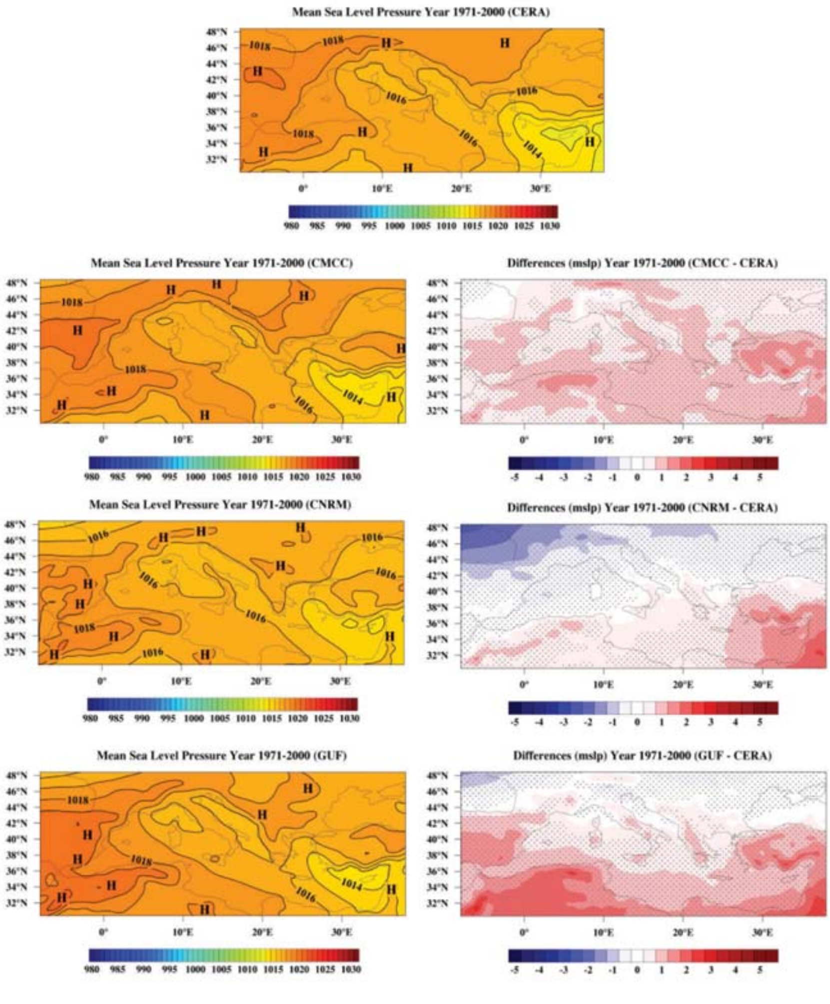

Fig. 1. Spatial distribution of CERA data for SLP values on an annual basis. Spatial SLP distribution of the three exam-

ined RCMs (left column) and their differences in comparison to the CERA data (model – CERA) (right column). The statistically significant differences are marked with grey points (t-test: 0.05 level).

3.2 Wind fields analysis

According to the annual distribution of wind speed over the domain of interest, as illustrated in Fig. 2, the CERA database depicts a pattern where the most intense winds are found over the sea, while over land the wind speeds are rather lower. The maximum is observed, as expected, over the Aegean Sea with the wind speed reaching 8 m/sec. A secondary maximum is found over the Marseille area in France (Gulf de Lion), as well as in the area between Sardinia and Tunisia. The maximum over the Aegean region could be attributed to the Etesian Winds during summer as well as the strong north winds that prevail over the area in winter. Moreover, the other maximum is found in one of the most characteristic centers of deep depression formation over the Mediterranean region, which could be associated with high speed winds. The evaluation of the three examined models in simulating the winds over the Mediterranean showed in general an efficient skill in reproducing the spatial distribution of their velocity value (Fig. 2). The gulf of Lion is the region where all models reproduce the highest wind speed values up to 8 m/sec while the Aegean Sea is the second part of the Mediterranean where the winds blow in high speeds. However, conversely to the CERA database where the island of Crete is also characterized by intense winds, the models were not able to reproduce this kind of a pattern. In all three models, the wind speed seems to diminish over the land of Crete, while at the west and east of the island their velocities remain high. Another difference of the RCM outputs is the existence of more intense wind at the Straits of Gibraltar, which is not detected in the CERA annual wind map (Fig. 2). Regarding the continental parts of the domain of study the CMCC and the GUF models simulate slightly higher wind speeds especially in some parts of the Balkan Peninsula and the mountainous areas of the Iberian Peninsula. On the other hand, the CNRM model reproduces quite weaker winds over Spain, Italy and Greece.

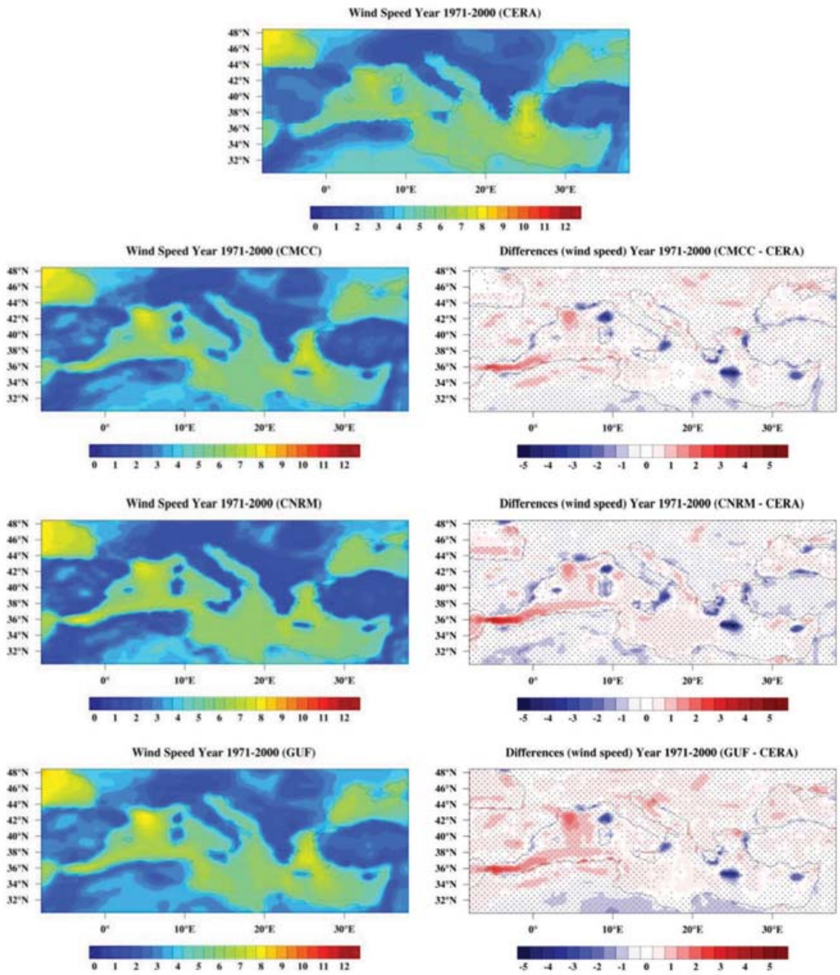

Fig. 2. Spatial distribution of CERA data for wind speed (m/sec) on an annual basis. Spatial wind speed distribution of the three examined RCMs (left column) and their differences in comparison to CERA data (model – CERA) (right column). The statistically significant differences are marked with grey points (t-test: 0.05 level).

3.3 Evaluation of extreme SLP Systems: Deep Depressions over the Mediterranean region

According to the annual results from the CERA data base, deep cyclones characterize a quite large part of the Mediterranean region, especially over the sea. For most of the grid points the frequency of occurrence of deep depressions does not exceed 5 days during the 1971-2000 period. However, it is obvious that there are center regions where these frequencies are higher (Fig. 3). The maximum is found over two of the most well know regions of Mediterranean cyclogenesis, such as the Gulf of Genoa (Ligurian Sea) and the Gulf of Venice in the Adriatic Sea. In these areas, the frequency of "extreme" depressions reaches 10 days (2nd class) and for some grid points (in aforementioned regions, as well as the Gulf of Taranto in southern Italy) there frequency is even higher up to 15 days. Finally, grid points with 2nd class frequency of occurrence are detected north of Cyprus in northeast Black Sea, as well as in the center of the Tyrrhenian Sea. Regarding the CMCC results, it is found that the model is able to reproduce the main centers of deep depression formation over the domain of study. However, the grid points that satisfy the aforementioned criteria are more in comparison to the CERA results. Furthermore, a larger number of grid points have frequencies of the 10 to 15 days class (two are found over the Aegean Sea and one over the Gulf of Lion) and the grid point located over the Gulf of Venice had almost 20 days of "extreme" depressions (Fig. 3). In the CNRM model case, the distribution of the frequencies of deep cyclones is quite similar to the CERA one, with the main centers over the Gulfs of Genoa and Venice, and the centers of the Tyrrhenian Sea and Adriatic Seas (Fig. 3). However, the absolute maximum is shifted to the west, in comparison to the CMCC model, where the grid with a frequency of 20 days of deep depressions is located at the Gulf of Genoa. Finally, the equivalent annual results of the GUF model are mainly analogous to the CMCC model, especially regarding the frequency maxima. In general, this model is quite capable in reproducing the areas where deep depressions mainly occur, indicating also three grid points over the Aegean Sea with frequencies up to 10 days and one over the north Black Sea with frequencies in the third class (10 to 15 days).

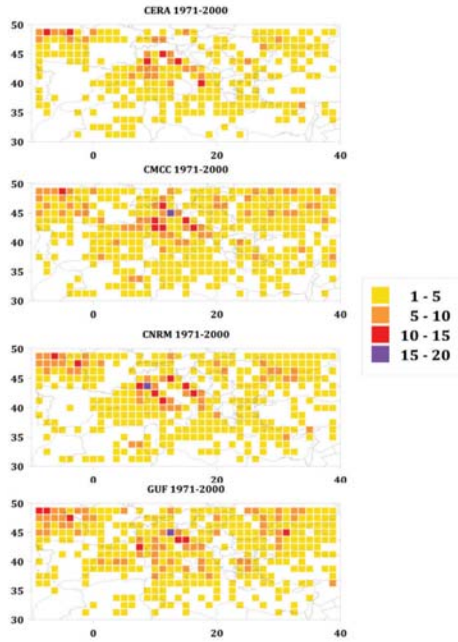

Fig. 3. Frequencies of occurrence (number of days) of the deep depressions over the Mediterranean Sea on an annual

3.4 Evaluation of the storm surge model in the Mediterranean coastal zone

Fig. 4 presents comparisons of 10-year averaged SSH maxima in 5 Greek stations for one of the RCM forcing of MeCSS against *in situ* data by the HNHS (http://www.hnhs.gr/portal/page/portal/HNHS). MeCSS model's skill ranges from acceptable to good in certain areas having a Pearson correlation coefficient, root-mean-square error and Willmott Skill Score of 0.89, 0.037 m and 0.78, respectively. Characteristic CMCC-forced MeCSS model results for the 30-year Reference Period are also presented as inter-annual SSH maxima throughout the entire Mediterranean coastal zone. The northern Adriatic Sea and the Gulf of Gabes seem to be the most affected areas, with storm surge levels up to 0.5 m.

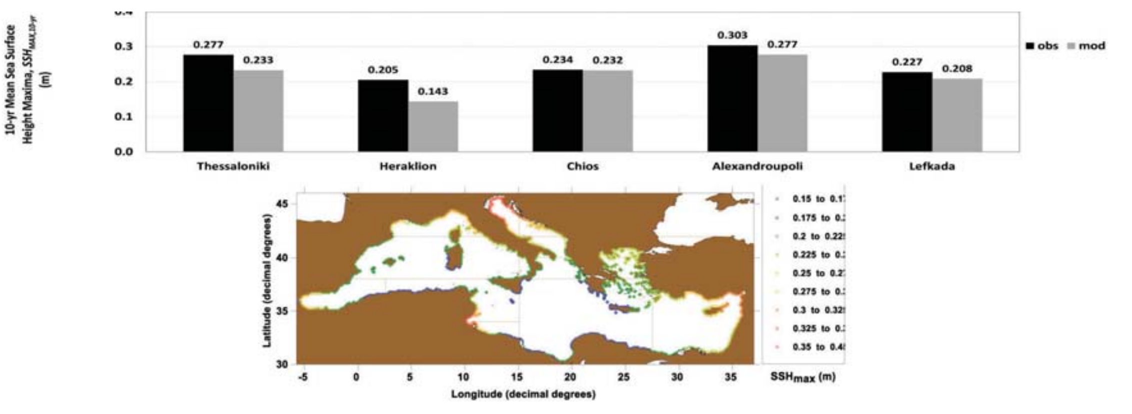

Fig. 4. A) Comparison of 10-yr average SSH_{MAX} (m) in 5 Greek stations between CMCC-forced MeCSS model (mod) and field (obs) data. B) Map of coastal storm surge impact $SSH_{MAX,30\text{-}yr}$ (m) for the Reference Period.

4 Conclusions

The evaluation of the examined models in simulating both the SLP and wind fields on an annual scale revealed that all three of them showed in general an efficient skill in reproducing both the spatial distribution as well as the magnitudes of these parameters. Regarding the Mediterranean deep depressions overall the models were able to reproduce the areas where deep depressions mainly occur. Finally, the CMCC-forced MeCSS model pointed out two areas (northern Adriatic Sea and the Gulf of Gabes) that are mainly affected from the storm surges.

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