Interreg Italy - Croatia RESPONSe

EUROPEAN UNION

DELIVERABLE 3.2.1

Climate change projections assessment: Analysis of regional climate models' simulations

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Project key facts

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Specific objective:	2.1 Improve the climate change monitoring and planning of adaptation measures tackling specific effects in the cooperation area
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Final	31.03.2020	DHMZ	Numbers check and minor revision done.

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Introduction

For the Activity 2 *Analysis of regional climate models' projections and bias adjustment* in the WP3, the RESPONSe Application Form (AF) plans following activities:

> *"Comprehensive analysis of the results of the RCMs from the Med-CORDEX and EURO-CORDEX initiatives will be performed for the project regions. The focus will be given to 12.5 km simulations, to available referent concentration pathway scenarios and two future periods (2011-2040 and 2041-2070) with respect to the historical climate (1971- 2000). Changes and trends in mean and extreme variables will be explored for 2-m air temperature, total precipitation amount, 10-m wind speed, sea level, temperature and salinity. For the period 1971-2000, results will be compared against the local observations.*
>
> *RCM simulations considered will be subjected to a statistical post-processing through an empirical Quantile Mapping (QM):.(1) regional-based QM, and (2) station-focused QM application, Both the applications will be configured in order to preserve original simulations' climate change signal."*

This deliverable is focused to the analysis of the raw output of the regional climate models and literature review of additional results with the focus over the Adriatic region.

More specifically, AF defines the general scope of this deliverable as:

> "*It reports on relevant results based on the output of the RCMs. Focus on pilot areas, but will provide general and regional overview similar to D3.1. For projected climate change signals over the Adriatic basin, estimates of the uncertainty and the time-of-emergence of significant climate shifts will be provided based on the existing combinations of the global climate models, RCMs and applied greenhouse-gases emission scenarios. Suggestions for further development of RCMs will be given.*"

The part related to the development of the bias-corrected datasets is presented in the deliverable D3.2.3. The results of the atmosphere only RCMs simulations extracted for the RESPONSe pilot areas are part of the deliverable D3.2.2. The original atmosphere only RCM data are retrieved from the Earth System Grid Federation (ESGF) and repozitorij.meteo.hr databases, while data from the coupled atmosphere-ocean RCMs are retrieved from the www.medcordex.eu database.

Climate change projections

1 Mean climate change projections over Adriatic region

METHODOLOGY

The spatial resolution of the Regional Climate Models (RCM) used in this subsection is 12.5 km, which is ensuring a realistic appreciation of the basic spatial characteristics throughout the Adriatic region. The temporal focus of the analysis is the period 1971 to 2070. Boundary conditions for the applied RCMs are the results of Global Climate Models (GCMs), in this case the results of four CMIP5 GCM. One specific projection of the future climate is the combination of one RCM (out of 3 selected in this analysis), one GCM (out of 4 selected in this analysis), and one scenarios (out of 2 selected in this analysis). Finally, we analyse 12 historical simulations climate and 24 simulations of the future climate.

RCMs are state of the art research tools whose development began in the late 1980s (e.g., Giorgi and Mearns 1991**,** Laprise et al. 2008**,** Rummukainen 2010, Prein et al. 2015, Rummukainen 2016, Giorgi 2019). Some basic settings in the simulations used in the analysis presented in this deliverable include:

1. The applied spatial resolution of 12.5 km makes it possible to represent the main topographic features and the basic structure of the land-sea border.
2. The global and regional climate models apply observed greenhouse gas concentrations over the historical period (1971-2005) and two possible scenarios for the future climate (RCP4.5 and RCP8.5; van Vuuren et al. 2011), representing a moderate and extreme (and low probability) scenarios, between which larger differences are expected from the mid-21st century onwards. It is important to emphasize that with these two scenarios one cannot expect to keep the global warming below 1.5 °C compared to the end of the 19th century.
3. The use of three regional and four global climate models takes into account the spread in simulating the climate system associated with the formulation of the climate model and by making specific assumptions. An advantage of the approach used here is the complete combination matrix where all three RCMs are separately forced with each of the four GCMs selected. Using multiple models is recommended approach to avoid dependency on assumptions and implementation details of only one model.
4. The models are comparable to the observations in terms of the mean climate (not in terms of simulating a particular time event, month, season or year). Future climate simulations should be interpreted as a projections based on the boundary conditions.

GCMs applied in forcing the RCMs analysed in this deliverable are:

1. **MPI-ESM-LR/MPI-ESM-MR**: http://www.mpimet.mpg.de/en/science/models/mpi-esm/
2. **EC-EARTH**: http://www.ec-earth.org/about/
3. **CNRM-CM5**: http://www.umr-cnrm.fr/spip.php?article126&lang=en
4. **HadGEM2-ES**: https://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadgem2

From the EURO-CORDEX initiative (Jacob et al. 2014, Kotlarski et al. 2014) following two RCMs are used:

1. **RCA4**: https://www.smhi.se/en/research/research-departments/climate-research-rossby-centre2-552/rossby-centre-regional-atmospheric-model-rca4-1.16562
2. **CCLM4**: https://wiki.coast.hzg.de/clmcom

Data from the third RCMs,

3. **RegCM4** (https://www.ictp.it/research/esp/models/regcm4.aspx)

are result of the MZOE (2017) project, designed according to the EURO-CORDEX protocol and available through the database repozitorij.meteo.hr .

The basic limitation of climate models is the existence of the systematic errors when compared to observations. This is a limitation present in all climate models and is addressed by the development of climate models (e.g. increase of the spatial resolution, introduction of additional processes and development of individual models' parts). In the case of regional climate models forced by global climate models, these discrepancies can be analysed at the level of mean climatology (e.g. a mean of 20 or 30 years compared between models and observations). As a source of measured data, users and researchers use data from meteorological stations and more recently from the gridded datasets obtained by the geostatistical interpolation methods. Air temperature at 2 m and total precipitation from EURO-CORDEX regional climate models (including RCA4 and CCLM) were analysed in detail with respect to the E-OBS observations in Kotlarski et al. (2014). Also, the results of the DHMZ RegCM4 simulations are by a comparable methodology documented in Güttler et al. (2020). Generally, model performance varies from model to model and depends on:

1. the area analysed,
2. the time of year (e.g. season) and the period analysed,
3. the variables analysed,
4. evaluation metrics applied.

Averaged over larger geographical areas, mean air temperature errors at 2 m are typically in the range of -1.5 °C to 1.5 °C and mean errors of total precipitation of -40% to 40% (Kotlarski et al. 2014). Depending on location and model, systematic errors of the significantly less amplitude are possible. To avoid dependence on constraints within just one regional climate models, it is recommended to use a set (ensemble) of regional climate models. Using a relatively large set of 12 combinations of regional and global climates models in this deliverable, we are addressing systematic errors and significantly reduce the dependence on assumptions and approximations within individual combinations of regional and global climate models.

RESULTS

In the next two subsections we analyse the change in a near-future climate (P1 (2011 – 2040)) and mid-future climate (P2 (2041 – 2070)) in respect to historical climate (P0 (1971 – 2000)). Both temperature and precipitation change is shown as a mean (Fig 1.1 – Fig 1.4) and median change (Fig 1.5 – 1.8) for two RCP (RCP4.5 and RCP8.5) scenarios.

TEMPERATURE

The mean and median ensemble temperature values for P0 are in general the same above domain.

Ensembles indicates the air temperature for DJF in the range from 0 to 5 °C in inland, over a mountainous region in the range from -5 to 0 °C, while over coastal and sea areas from 5 to 10 °C. During the MAM, temperature is in a range from 5 to 10 °C over the inland of Croatia and from 10 to 15 °C over coastal areas and Italy. Values bellow 5 °C are only over mountainous regions. During JJA, the temperature is in a range from 15 to 20 °C over complex areas (i.e. higher hills) and 20 to 25 °C over narrow continental and coastal areas. Over mountainous regions the temperature is bellow 10 °C. During SON the temperature values are close to MAM season values, i.e. 5 to 10 °C over higher hills and 10 to 15 °C over narrow continental, coastal areas and Italy, with exception for temperatures above sea (values from 10 to 15°C).

In respect to historical climate (P0), in a near-future climate (P1) for RCP4.5 scenario the increase of temperature is expected, in both, the median and mean ensemble, for all seasons. The relative mean change (P1-P0 and P2-P0) is much smoother (Fig 1.1 - Fig 1.2) than the median change (Fig 1.5 - Fig 1.6). The highest increase is expected during JJA (1 to 1.5°C) while during all tree other seasons (DJF, MAM and SON) expected temperature increase is between 0.5 and 1°C. In a mid-future climate (P2) temperature increase is also expected in both ensembles for all seasons. The lowest expected increase is for MAM (in general 1 to 1.5 °C for both ensembles) followed by SON and DJF (in mean ensemble generally all domain around 1.5 °C, in median ensemble values mainly from 1.5 to 2.0 °C, but up to 2.5 °C) and JJA (for both ensembles 2 to 2.5 °C up to 3,0 °C).

For RCP8.5 scenario, the increase of temperature in P1 is overall in the same range as for RCP4.5 for both ensembles. The lowest increase is expected for MAM (0.5 to 1 °C) which is followed by SON (entire domain generally close to 1 °C), DJF (up to 1.5 °C mainly over inland) and JJA (generally 1 to 1.5 °C). In P2, the temperature change in both, mean and median, ensembles is much intensive than for P1 (RCP8.5) and P2 for RCP4.5 scenario. The highest temperature increase is expected for JJA (2.5 to 3 °C over continental areas), a bit lower for DJF (above 2.5 °C mainly over mountainous regions while other continental areas 2 to 2.5 °C), further lower increase for SON (generally entire domain around 2.5 °C) and lowest temperature increase for MAM season (2 to 2.5 °C).

PRECIPITATION

Median and mean ensemble values of daily precipitation (Fig 1.3 – 1.4, Fig 1.7 – 1.8) indicate the same range of values over the domain for the historical climate (P0).

During the JJA, models tend to give small amounts of precipitation over the domain (0 to 1 mm/day over the south Italy and sea and 2 to 5 mm/day over complex terrain), while during SON models simulate more precipitation (2 to 5 mm/day generally over entire domain except over mountain parts (5 to 10 mm/day)). During DJF and MMA precipitation is in a range from 2 to 5 mm/day over continental parts, 5 to 10 mm/day over mountainous regions (even 10 to 20 mm/day during DJF in the eastern part of domain), and 1 to 2 mm/day over sea.

RCP4.5 scenario in P1 generally gives a gently increase in precipitation amount for all seasons except for JJA and the sign of change is the same for both ensembles. The relative change for DJF, MAM and SON is mostly around 5%, while JJA decrease is between -5 and -10%. Similar changes are expected in mean ensemble for P2. For the median ensemble a moderate increase in gradients over the domain is found for P2. Differences in JJA and SON are up to 20% (JJA -20%, SON +20%).

RCP8.5 scenario produces similar change in precipitation as RCP4.5. In P1, the change over the domain is more or less the same as for RCP4.5 for the mean ensemble, while for the median ensemble, in southern parts of the domain (mainly over Italy), coastal areas and over sea, a change in sign is found for DJF and MAM seasons. However, over the entire domain, the change in precipitation for P1 for DJF, MAM and SON is mainly in a range from -5 to 5% (up to 10%) and for JJA mainly in a range from -5 to -10% (up to -20%).

For P2 in mean ensemble, the decrease in precipitation during JJA is more obvious (-20 to -10%), mainly in southern parts of the domain, while in DJF a moderate increase is expected (5 to 10%). During SON and especially MAM, the mean ensemble signal is mixed over the domain, and in a range from -10 to 10%.

For median ensemble, the sign of change is the same and for P2 even more evident for all seasons. In general, the mean ensemble tends to smooth contours of precipitation over domain, while median tends to show higher gradients.

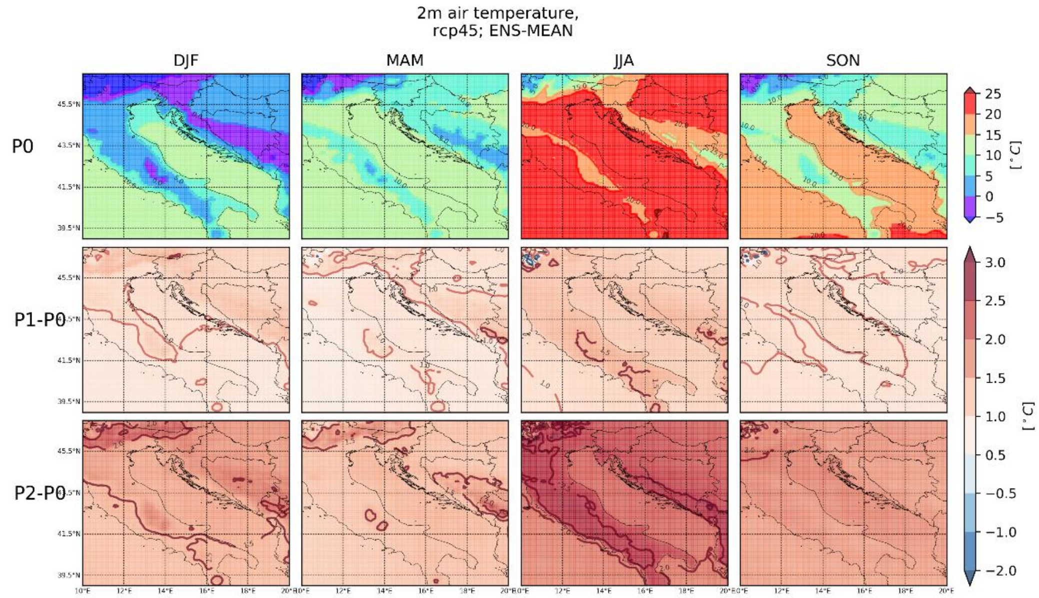

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Figure 1.1: The ensemble mean 2 m air temperature (in °C) from EURO-CORDEX projection in the present climate P0 (1971-2000) shown in the 1st row. Projected change in the near future P1 (2011-2040) w.r.t. P0 in the 2nd row. Projected change in the mid-21st century P2 (2041-2070) with respect to (w.r.t.) P0 in the 3rd row. Scenario: RCP4.5. The results are displayed for each season separately (columns from left to right: winter/DJF, spring/MAM, summer/JJA, autumn/SON).

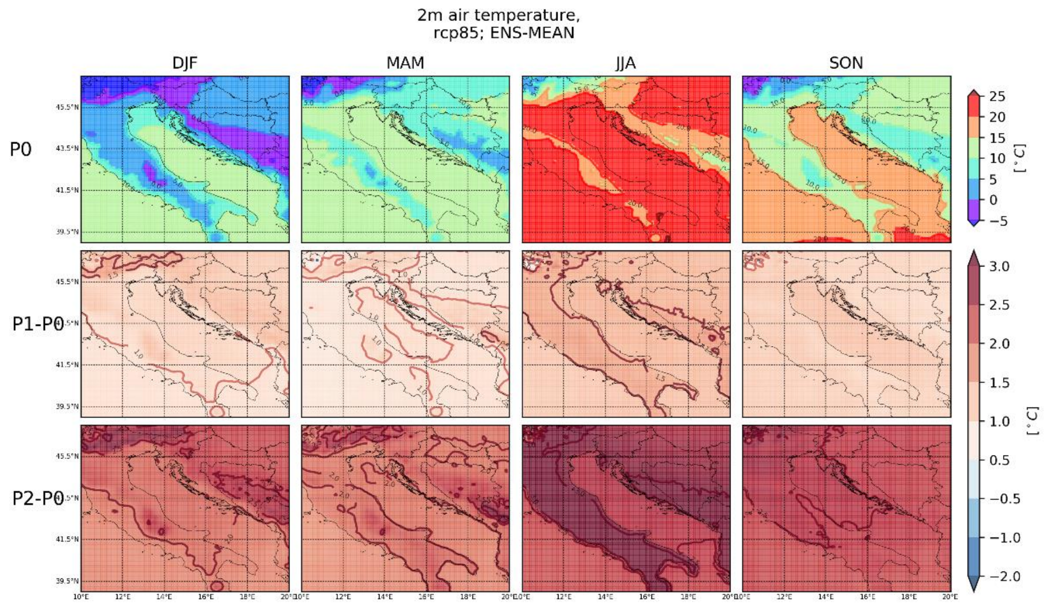

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Figure 1.2: Same as Fig. 1.1 but for the scenario RCP8.5.

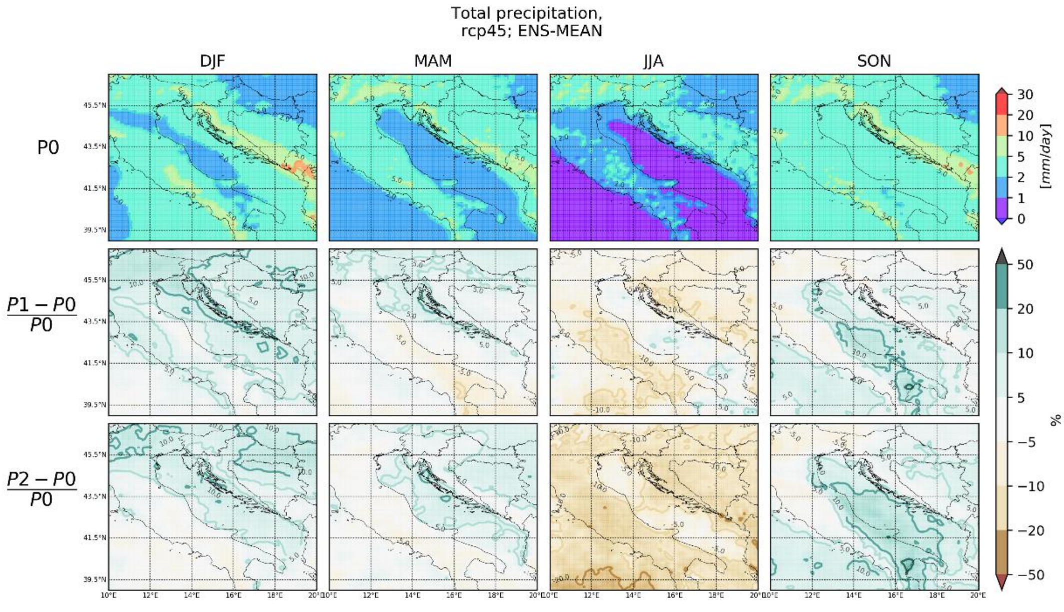

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Figure 1.3: The ensemble <u>mean</u> total precipitation amount (in mm/day) from EURO-CORDEX projection in the present climate P0 (1971-2000) shown in the 1st row. Projected relative change in the near future P1 (2011-2040) w.r.t. P0 in the 2nd row. Projected relative change in the mid-21st century P2 (2041-2070) w.r.t. P0 in the 3rd row. Scenario: RCP4.5. The results are displayed for each season separately (columns from left to right: winter/DJF, spring/MAM, summer/JJA, autumn/SON).

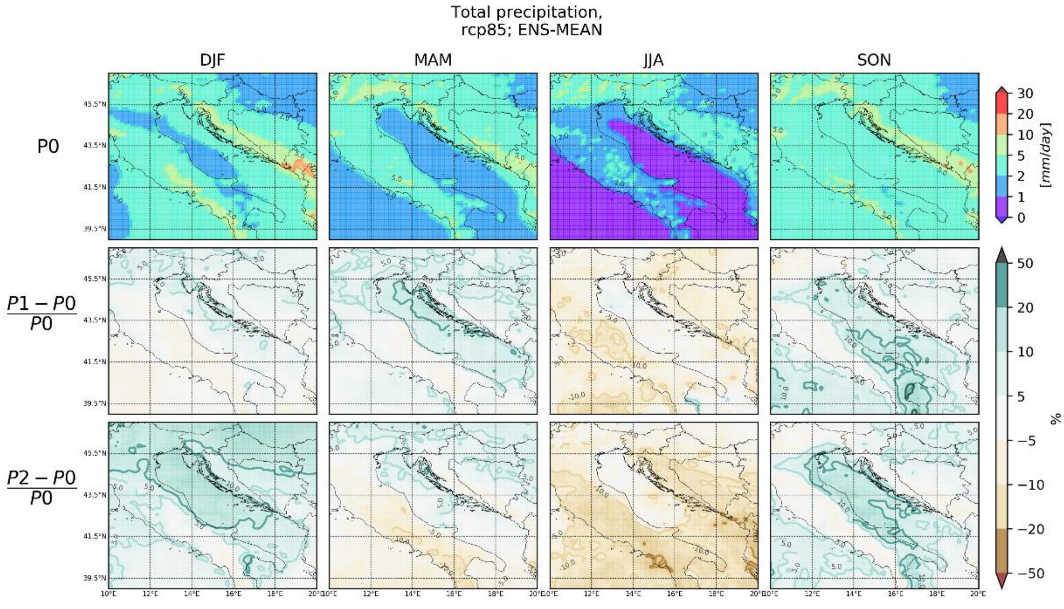

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Figure 1.4: Same as Fig. 1.3 but for the scenario RCP8.5.

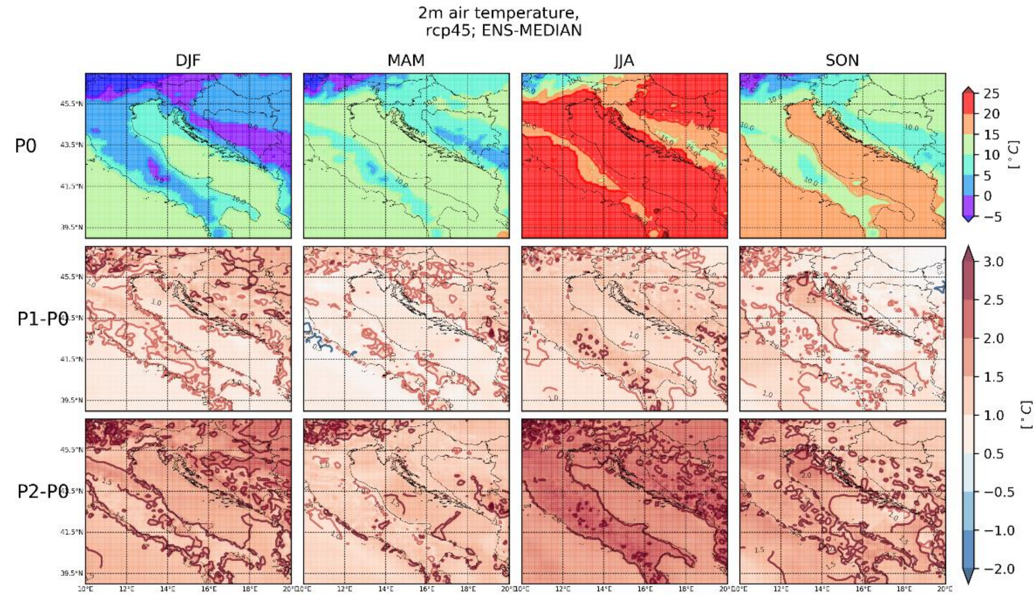

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Figure 1.5: The ensemble <u>median</u> 2 m air temperature (in °C) from EURO-CORDEX projection in the present climate P0 (1971-2000) shown in the 1st row. Projected change in the near future P1 (2011-2040) w.r.t. P0 in the 2nd row. Projected change in the mid-21st century P2 (2041-2070) w.r.t. P0 in the 3rd row. Scenario: RCP4.5. The results are displayed for each season separately (columns from left to right: winter/DJF, spring/MAM, summer/JJA, autumn/SON).

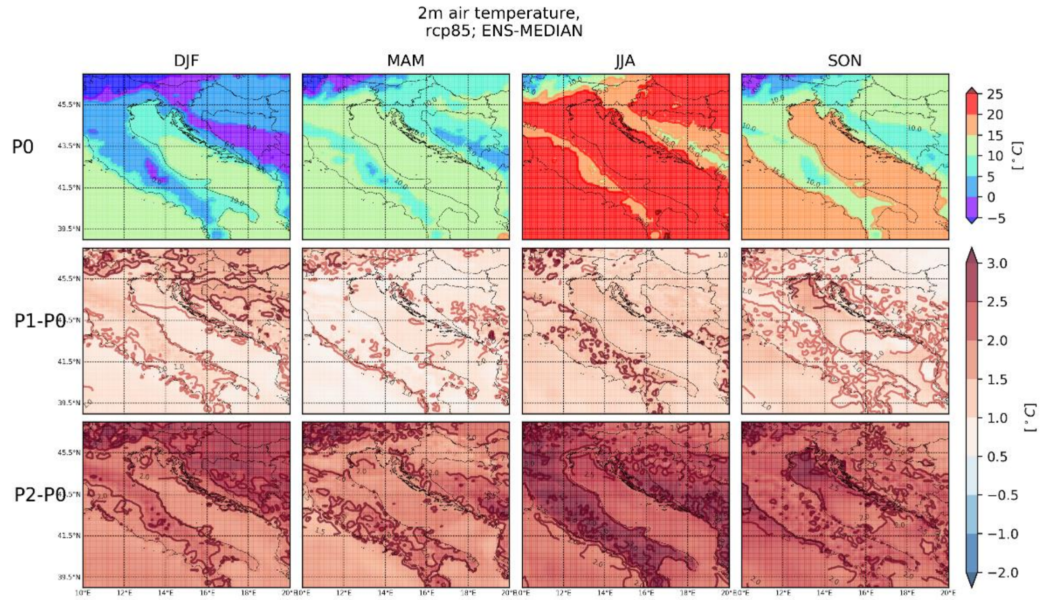

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Figure 1.6: Same as Fig. 1.5 but for the scenario RCP8.5.

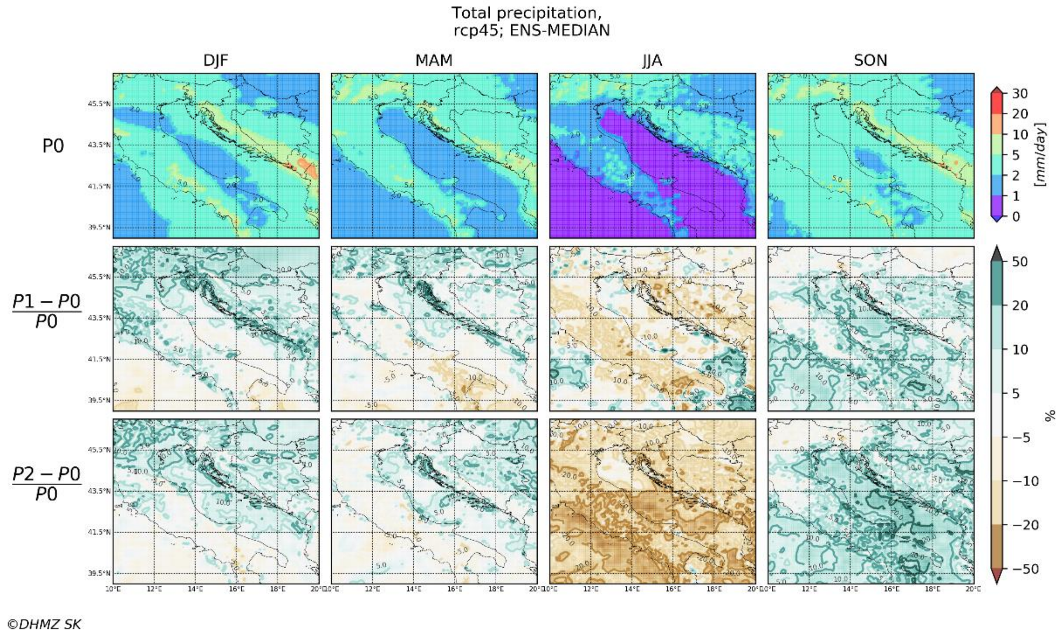

Figure 1.7: The ensemble median total precipitation amount (in mm/day) from EURO-CORDEX projection in the present climate P0 (1971-2000) shown in the 1st row. Projected relative change in the near future P1 (2011-2040) w.r.t. P0 in the 2nd row. Projected relative change in the mid-21st century P2 (2041-2070) w.r.t. P0 in the 3rd row. Scenario: RCP4.5. The results are displayed for each season separately (columns from left to right: winter/DJF, spring/MAM, summer/JJA, autumn/SON).

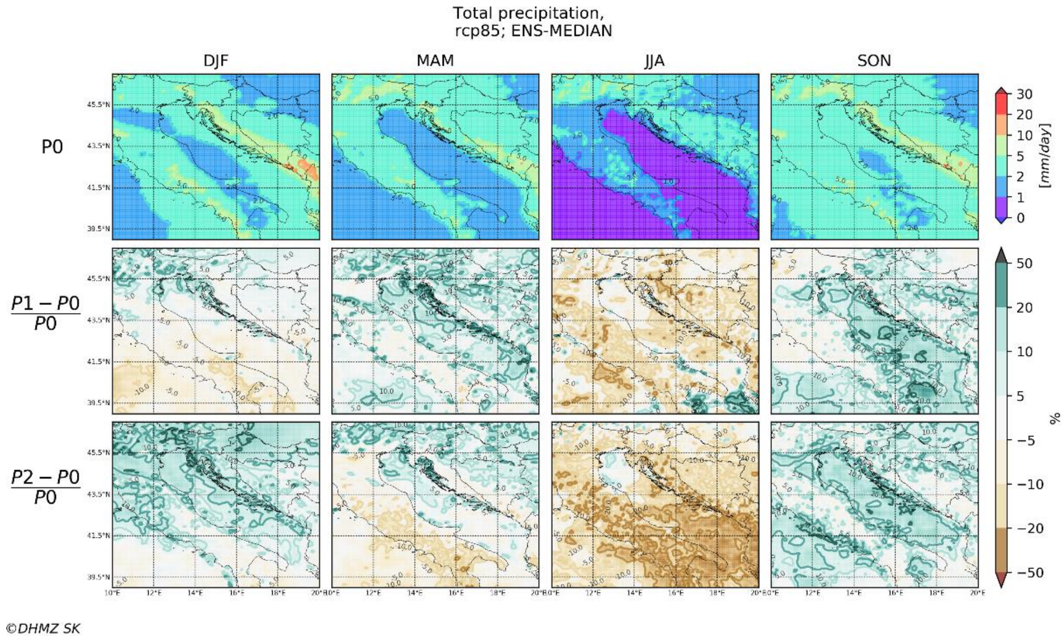

Figure 1.8: Same as Fig. 1.7 but for the scenario RCP8.5.

WIND

This subsection provides a brief summary of the climate change projections analysis based on the Belušić Vozila et al. (2018) study.

In comparison to temperature and precipitation analysis performed for the purpose of this deliverable, Belušić Vozila et al. (2018) apply seven EURO-CORDEX models at 0.11°/12.5 km grid spacing covering the Adriatic domain (cf. their Table 1 for the list and references to all applied RCMs). In total, they analyse an ensemble of 19 simulations for two (RCP4.5 and RCP8.5) greenhouse-gases scenarios to provide climate change estimates in the 10 m winds. Their ensemble includes also simulations of the three RCMs analysed in the previous subsection.

While Belušić Vozila et al. (2018) primarily focus to the analysis of two specific wind types (Bura/Bora and Jugo/Sirrocco; interested reader is referred to the original study), Fig. 1.9 (Fig. 4 in Belušić Vozila et al. 2018) provides estimates of the extreme wind speed projections over the Adriatic domain including all RESPONSE target areas.

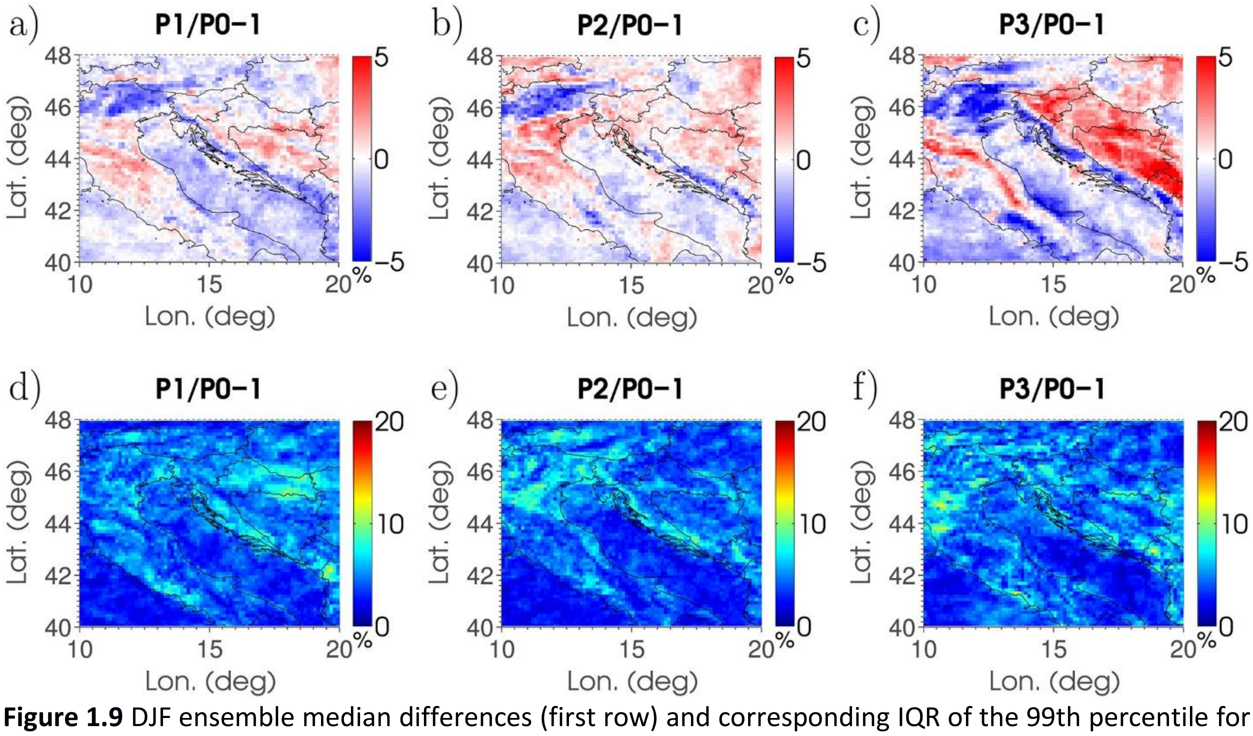

Figure 1.9 DJF ensemble median differences (first row) and corresponding IQR of the 99th percentile for the wind speed in the RCP8.5 scenario (second row). The ensemble consists of 19 members, except for P3, which has 15 members. Relative differences in (a, d) P1, (b, e) P2, and (c, f) P3 compared to P0. DJF = December-January-February; IQR = interquartile range; P0 = 1971–2000; P1 = 2011–2040; P2 = 2041–2070; P3 = 2071–2099 (Figure 4 from Belušić Vozila et al. 2018).

Changes in higher percentiles (e.g., 99th percentile) of the daily wind speed are relevant parameters to assess future climate change projections in 10 m wind speed extremes from the ensemble of RCMs (Rockel & Woth, 2007). Belušić Vozila et al. (2018) found that the spread of the results between the RCMs is not homogeneous throughout the year (their Figures 4 (for winter) and S3.3 (for summer); Fig. 1.9 in this deliverable (for winter)). Also, specific simulations do not agree on the location or sign of the most intense climate change over the Adriatic. However, by taking the ensemble median separately for each season, a few regions with consistent signals emerge in the RCP8.5 scenario (similar results are also found in the RCP4.5 ensemble but with the lower amplitude). Several conclusions are made by the authors, with the main one related to the relationship between the simulated climate change signal on the level of the ensemble median, and associated measure of the ensemble spread, i.e., the interquartile range: the climate change signal in the extreme 10m wind as captured by the 99th percentile emerges from the ensemble spread only in the latest period in the 21st century. Supported by these results, we may conclude that the area wide changes in the wind speeds over the Adriatic region by the end of the 21st century are low. As a recommendation for the scientific community, similar type of analysis should be revisited using convection-permitting regional climate models at the kilometre scale horizontal resolution which can capture more details in the local wind flow dynamics.

2 Climate change projections and impact on tourism activities

Climate has a key role in defining resources for any kind of tourism. Mediterranean is one of the most visited tourist destinations and therefore it is very important to study its vulnerability to climate change. Amengual et al. (2014) studied projections of the climate potential for beach-based tourism in the Mediterranean. They considered climate index for tourism (CIT) based on ensemble of 13 regional climate models from ENSEMBLES project in the period of 1951-2100. Future climate has been considered for A1B SRES[1] emissions scenario. Climate change of mean absolute frequencies of acceptable and ideal condition has been studied for three 20-year future time slices (2015-2034, 2045-2064 and 2075-2094) according to the referent present climate (1990-2009). At the end of 21st century the annual number of days rated as acceptable will increase along the Mediterranean coastline. Along the Adriatic coastline (Italy and Croatia) the increase of the acceptable days could be close to a month per year but, in general, for the central part of Mediterranean a deterioration of ideal climate conditions for tourism is projected. Along the Adriatic coast changes in seasonal regimes of climate potential for 3S tourism (i.e., Sun, Sea, Sand) indicate moderate decrease in the number of days with acceptable conditions but increase in the number of days with ideal conditions in spring. Ideal climate conditions in summer could decrease close to 30 days per season, but the same amount could be seen as an increase in acceptable conditions. In autumn, there is no change in acceptable conditions and a small increase of ideal conditions.

Bafaluy et al. (2014) studied climate and climate change impacts on other types of tourism activities (cycling, cultural, football, golf, motor boating, sailing and hiking) for the Bay of Palma, Spain. Data set used to study climate change of these activities was the same as in Amengual et al (2014) who studied projections of the climate potential for beach-based tourism in the Mediterranean in 21st century. Football, as the most popular outdoor activity in the present climate, is expected to stay the most suitable outdoor activity with a more than half of annual days with ideal conditions. On the annual scale conditions for cycling, hiking and cultural tourism will show slight degradation because of transition from acceptable into unacceptable conditions while at the same time projected ideal conditions for those activities will remain the same as in present till the end of 21st century. Both, motor boating and sailing are projected to increase ideal conditions to the end of 21st century, and projections for golf, activity that in the present has the lowest percentage of ideal conditions in the annual relative frequencies, show that ideal conditions will have no significant change. Changes in seasonal regimes of climate potentials for cycling show that conditions will become more unsuitable in summer and more suitable during spring and autumn with no significant changes in winter. For cultural and football activities winter conditions will not change or will change with a minor extent. For both activities (cultural and football) the most suitable seasons will remain spring and autumn, whereas in summer touristic potential would degrade. Climate potential for golf will decrease in winter and slightly increase in summer, but the most suitable conditions will remain in spring and autumn. Climate potential for motor boating will increase in all seasons. Sailing climate potential will decrease slightly in summer, with the best sailing period in spring and autumn.

[1] SRES (Special Report on Emission Scenarios) scenarios preceded the RCP (Representative Concentration Pathways) and were used in Forth Assessment Report of the IPCC.

Hiking climate potential changes will be small mostly during summer when the ideal conditions will degrade.

Grillakis et al. (2016) studied 2 degree global warming effect on summer European tourism through different indices among which was CIT for general outdoor activities. Indices were calculated from ensemble of five CORDEX regional climate models driven with five global climate models for two different scenarios RCP4.5 and RCP8.5. Present climate period was 1971-2000, and future 30-year time slice was defined for each driving GCM on the following way: the 30-year period around +2 °C warming comparing to the preindustrial baseline period 1881-1910. For RCP8.5 the period is between 2016 and 2045, and for RCP4.5 between 2037 and 2066. They considered two time periods, from May to October, as the late spring, summer and early autumn season and from June to August what is the high season of tourism activities in Europe. For Adriatic regions in present climate CIT is rated from acceptable to ideal in both periods within the year, with slightly increased climate comfort in summer. The signal of projected change for CIT will increase between 5 and 10 % regarding two considered RCPs scenarios. 27 European countries were considered, among them was Italy. For both periods (MJJASO and JJA), the CIT results show that climate will be more favourable in all considered European countries except Cyprus and small Greek areas in JJA. Climate favourability for The Mediterranean region is expected to increase more in period May to October than in period June to August.

3 Climate change projections and impact on heating & cooling activities

This section provides summary of a recent study by Spinoni et al. (2018) in which the authors have analysed changes in the heating and cooling needs over Europe in present and future climate.

HDD (heating degree day) and CDD (cooling degree day) are weather-related indicators of energy consumption demands for heating and cooling buildings, and they were used for investigation whether energy demand for cooling and heating buildings can be expected to increase or decrease under climate change until the end of this century.

In the study, HDD and CDD were computed using the same method that was used in the earlier study by Spinoni et al. (2015) on European degree-day climatologies and trends during recent decades, as well as in a major study of global warming impacts on residential heating and cooling demand in the United States (Petri and Caldeira, 2015). Using this method, which was developed by the UK Met Office in 1928 (CIBSE, 2006), daily HDD and CDD are calculated based on a comparison of daily minimum and maximum air temperatures with the selected base temperature, taking account of fluctuations of daily air temperature around the base temperature, as well as the asymmetry between daily average temperature and diurnal temperature variations.

Table 3.1 UK Met Office equations for computing daily HDD by comparing daily maximum and minimum air temperatures (Tmax and Tmin) with a base temperature (Tbase). Daily average temperature (Tavg) is calculated as (Tmax + Tmin)/2. For this study, Tbase was set to 15.5°C.

Case	Condition HDD	HDD
1	Tmax ≤ Tbase (i.e. uniformly cold day)	Tmin ≥ Tbase (i.e. uniformly warm day)
2	Tavg ≤ Tbase < Tmax (i.e. mostly cold day)	HDD= [(Tbase − Tmin)/2] − [(Tmax − Tbase)/4]
3	Tmin < Tbase < Tavg (i.e. mostly warm day)	HDD= (Tbase − Tmin)/4
4	Tmin ≥ Tbase (i.e. uniformly warm day)	No heating is required, so HDD= 0

Table 3.2 UK Met Office equations for computing daily CDD by comparing daily maximum and minimum air temperatures (Tmax and Tmin) with a base temperature (Tbase). Daily average temperature (Tavg) is calculated as (Tmax + Tmin)/2. For this study, Tbase was set to 22°C.

Case	Condition CDD	CDD
1	Tmax ≤ Tbase (i.e. uniformly cold day)	No cooling is required so CDD= 0
2	Tavg ≤ Tbase < Tmax (i.e. mostly cold day)	CDD= (Tmax − Tbase)/4
3	Tmin < Tbase < Tavg (i.e. mostly warm day)	CDD= [(Tmax − Tbase)/2) − [(Tbase − Tmin)/4]
4	Tmin ≥ Tbase (i.e. uniformly warm day)	CDD= Tavg − Tbase

The input data for the study were generated by regional climate models (RCMs) participating in the EURO-CORDEX initiative. HDD and CDD values were computed directly from projected bias-adjusted daily minimum (TN) and maximum (TX) temperatures of 11 simulations (Dosio, 2016), and under two socio-economic scenarios based on two representative greenhouse gases concentration pathways, namely RCP4.5 and RCP8.5 (IPCC, 2014a, 2014b). RCP4.5 and the RCP8.5 data refer to the years 2006–2100, while historical data for the years 1981–2005 have been added to both scenarios. Quality checks and homogenization tests of the input daily temperature data have been performed using the MASH software (Szentimrey, 1999; Szentimrey, 2011). While normally not necessary for climate simulations data, these checks were made because the bias-adjustment procedure could potentially lead to inhomogeneities especially over regions with complex topography. Once quality checking was complete, mean temperature was computed by averaging minimum and maximum temperature values for each single day, grid point, and simulation.

The differences in degree-days between 2041-2070 and 1981-2010 periods over the Adriatic region

Concerning the heating and cooling needs in the recent past among six Adriatic locations under consideration, Cres, Šibenik, Lignano Sabbiadoro and Montemarciano are more similar between themselves then to Dubrovnik and Brindisi. Less heating and more cooling energy is needed in Dubrovnik and Brindisi then at other four locations. However, the differences between Dubrovnik and Brindisi energy needs are also rather big since Brindisi is much warmer than Dubrovnik over the whole year.

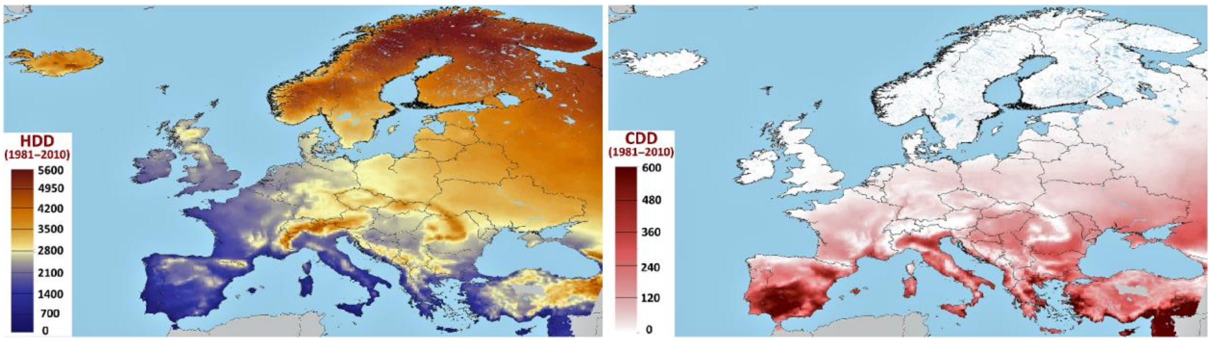

Figure 3.1 Ensemble mean values of HDD (left) and CDD (right) derived from 11 EURO-CORDEX simulations for recent past (1981–2010). (source: Spinoni et al., 2018).

A decrease in HDD in the mid-future (2041-2070) is, as expected, larger under RCP8.5 than under RCP4.5. In absolute values, the decrease in HDD is largest over north eastern Europe, with values between −800 and −1000, and smallest in southwestern Europe, where the decrease in HDD over the Mediterranean region is (on average) about −200 under RCP4.5 and −300 under RCP8.5. However, in percentage values, the decrease in HDD is largest in southern Europe, where values are projected to fall (on average) by 30% under RCP4.5 and 35% under RCP8.5.

In Europe the projected increase in CDD in the near future is not much different under RCP4.5 and RCP8.5, except over the Mediterranean region where it is larger under RCP8.5. In absolute values, the increase in CDD is generally much smaller than the converse decrease in HDD, which is due to the definition of HDD and CDD, and also because of the base temperatures chosen in the study. However, in percentage values, this situation is reversed for Spain, southern Italy, Greece, and Turkey, where the projected increase in CDD is greater than 40%, in particular under RCP8.5.

Table 3.3 Differences between average annual HDD and CDD in mid-future (2041–2070) and in recent past (1981–2010) under RCP4.5 and RCP8.5 scenarios at six Adriatic locations. (Interpolated values from Spinoni et al., 2018).

	Change in HDD (°C)		Change in CDD (°C)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cres	-200	-320	160	175
Šibenik	-200	-320	200	250
Dubrovnik	-200	-320	160	200
Lignano Sabbiadoro	-200	-320	200	250
Montemarciano	-200	-320	160	200
Brindisi	-200	-250	250	300

The differences in degree-days between 2071-2100 and 1981-2010 periods over the Adriatic region

RCP4.5 and RCP8.5 scenarios project a continuous decrease in HDD until the end of the 21st century, even though RCP4.5 assumes a stabilization of CO_2 equivalent after the early 2050s. The HDD values projected by the more moderate RCP4.5 for the far future are similar to those projected by the more extreme RCP8.5 for the near future. In absolute values, the RCP8.5 scenario projects a decrease of HDD of more than −800 for most of Europe, and of more than −1100 for large parts of northeastern Europe. In percentage values, under RCP8.5, the decrease in HDD ranges from −60% to −50% over southern Europe, and −35% to −45% over northern Europe. This change is expected to cause a significant reduction in energy demand. In summary, comparing projected HDD for the far future with that of the recent past, we can roughly identify a southwest to northeast gradient, from Lisbon to the Urals, of −1 HDD per 7km under RCP4.5, and −1 HDD per 5km under RCP8.5.

Under RCP4.5 the projected increase in CDD remains relatively stable between the near future and the far future, all over Europe, with an increase only evident over the Mediterranean area. Under the RCP8.5 the increase in CDD could be extreme over southern Europe, where CDD are projected to double in the far future compared with the recent past, or even climb by 300% or more in central and eastern Europe.

Indeed, the current CDD values for southern Italy and Greece could become normal for central France and Hungary by the end of the 21st century. In summary, comparing projected CDD for the far future with that of the recent past, we can roughly approximate a north to south gradient, from the latitude of Oslo to that of Malta, of 1 CDD per 9km under RCP4.5, and 1 CDD per 4km under RCP8.5.

Table 3.4 Differences between average annual HDD and CDD in far-future (2071–2100) and in recent past (1981–2010) under RCP4.5 and RCP8.5 scenarios at six Adriatic locations. (Interpolated values from Spinoni et al., 2018).

	Change in HDD (°C)		Change in CDD (°C)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cres	-300	-650	200	520
Šibenik	-300	-700	250	550
Dubrovnik	-300	-700	220	550
Lignano Sabbiadoro	-300	-650	250	550
Montemarciano	-300	-600	220	500
Brindisi	-250	-400	350	600

TREND ANALYSIS OF HDD AND CDD IN 1981-2100 PERIOD

The linear trends are expressed as the ensemble mean of the trends of the 11 EURO-CORDEX individual simulations.

The projected decrease of HDD is markedly larger under RCP8.5 than under RCP4.5 scenario for northern and eastern Europe. By the end of the 21st century, under RCP4.5 a decrease of more than −10 HDD per year is expected only in Scandinavia and Russia, whereas under RCP8.5 a decrease of more than −10 HDD per year is expected almost everywhere in central, eastern, and northern Europe. In Mediterranean region HDD decreases projected under RCP8.5 are also noticeably larger than projected under RCP4.5 scenario.

The latitudinal gradient of the projected increase of CDD is evident in Europe. For both scenarios the positive trend increases southwards, with the Mediterranean region showing the largest trends – up to about 4 CDD per year over great area of southern Spain under RCP4.5, and up to about 6 CDD per year under RCP8.5. Under both scenarios, southern, central and eastern Europe are likely to experience a progressively higher energy demand to cool internal environments as the century passes.

Table 3.5 Ensemble mean of the HDD and CDD trends and relative standard errors for Europe as a whole and Mediterranean region over the period 1981–2100. (Spinoni et al., 2018).

	HDD (°C/year)		CDD (°C/year)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Europe	−4.9 ±0.7	−8.4 ±0.7	0.8 ±0.2	2.0 ±0.2
Mediterranean region	−3.4 ±0.4	−6.1 ±0.3	1.9 ±0.2	4.4 ±0.2

Table 3.6 Linear trends of HDD per year and CDD per year under RCP4.5 and RCP8.5 scenarios at six Adriatic locations in 1981-2100 period. (Interpolated values from Spinoni et al., 2018).

	HDD (°C/year)		CDD (°C/year)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cres	-4	-7	2	5
Šibenik	-4	-7	2.5	6
Dubrovnik	-4	-7	2	5
Lignano Sabbiadoro	-4	-6	2.5	5
Montemarciano	-4	-5	2	5
Brindisi	-4	-4	3	8

4 Future climate of the Adriatic Sea

METHODOLOGY

Future climate of the Adriatic Sea was assessed by the Regional Climate System Model adapted for the Mediterranean region. Future potential scenarios were simulated with the latest available state-of-the-art fully-coupled climate model CNRM-RCSM4. The model includes a regional representation of the atmosphere (ALADIN-Climate model with 50 km resolution), ocean (NEMOMED8 model with 9-12 km resolution), land surface (ISBA model) and rivers (TRIP model), interconnected on a daily basis with the OASIS coupler (Sevault et al., 2014.). Atmosphere and ocean boundary conditions are taken from the Global Climate Model CNRM-CM5 (Voldoire et al., 2013), while concentrations of greenhouse gases (GHG) and aerosols are given by the International Panel for Climate Change (IPCC, 2013). Initial conditions are taken from the MEDATLAS 1960 database (Rixen et al., 2005). Besides scenario runs, three more simulations were made: spin-up period lasted for 100 years (1850 - 1950), historical simulation (HIST) from 1950 - 2005, and control simulation (CTRL) from 1950 - 2100.

Future development of the Adriatic Sea surface state was assessed for the two scenarios that are covering the period from 2005 till 2100. The scenarios are based on a various socio-economic assumptions given by the IPCC (IPCC, 2013) and are representing different so-called Representative Concentration Pathways (RCP). For the purpose of this work, two scenarios were selected: RCP4.5 and RCP8.5, labelled after a possible range of radiative forcing values in the year 2100. RCP4.5 is representing moderate-emission scenario with an increase of 4.5 W/m^2, while RCP8.5 is a high-emission scenario with an increase of 8.5 W/m^2 by the end of 2100.

Since no significant trends were found in control simulation, we can consider CNRM-RCSM4 a stable model. For all analysed hydrographic parameters, the assessment of potential future states was performed by comparing the two scenarios with the historical simulation. For this purpose we defined two future 30-year periods:

1. near-future (2011 - 2040), and
2. mid-future (2041 - 2070).

To single out climate signal from the natural variability incorporated in historical simulation, Confidence Interval (*CI*) for the 30-year period of the historical simulation (1971 - 2000), which is corresponding to 95% of significance level, was assessed. Anomalies are calculated as a differences between a scenario and a HIST simulation. All spatial distributions of anomalies are showing only those values that were found outside the *CI*, i.e. outside the interval.

In the following are analysed Sea Surface Temperature (SST), Sea Surface Salinity (SSS) and Sea Surface Height (SSH) of the entire Adriatic basin.

ADRIATIC SEA SURFACE TEMPERATURE

Averaged spatial SST distribution of the HIST simulation is successfully reproducing basic properties of the Adriatic Sea (minimum temperature found in the northern Adriatic, and maximum found near the eastern coast of Southern Adriatic, Artegiani et al., 1997a, Fig. 4.1).

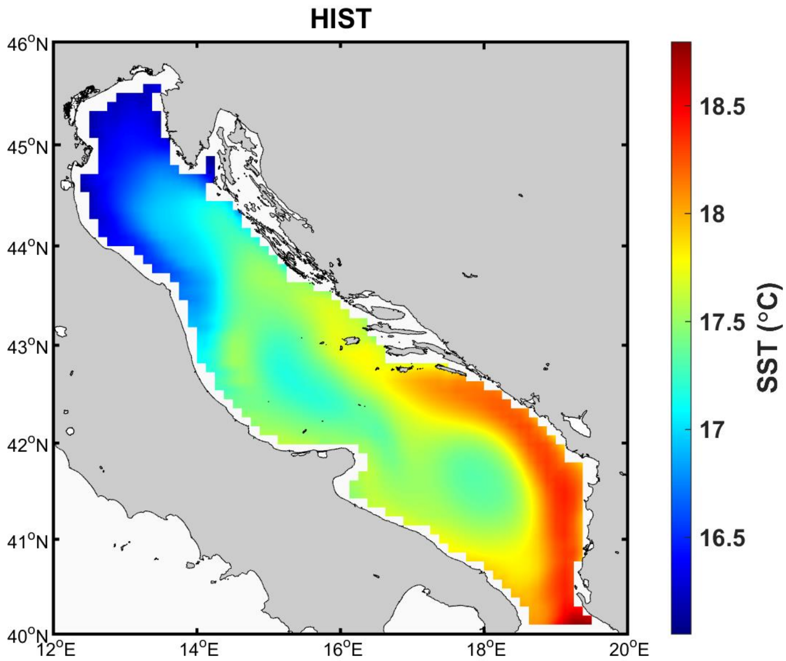

Figure 4.1 Sea Surface Temperature for the Adriatic Sea averaged over the 1971 - 2000 period of the historical simulation.

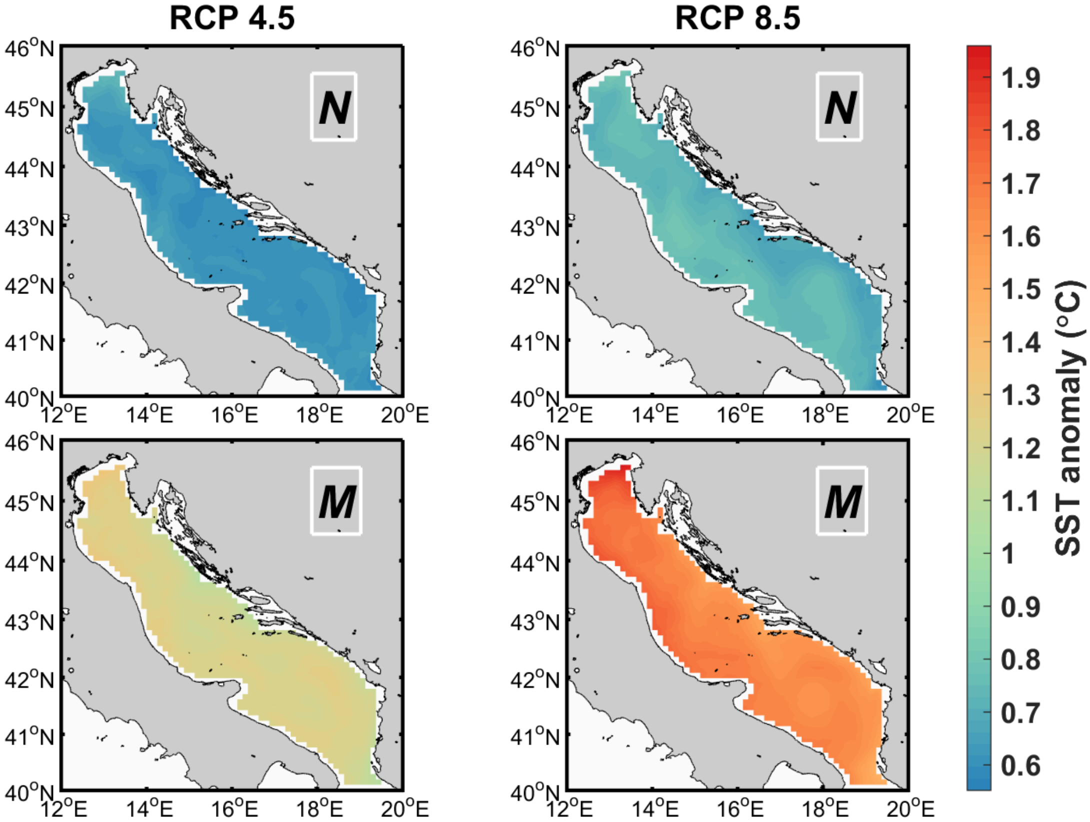

Figure 4.2 Sea Surface Temperature anomalies for the two defined periods (N - near future, M - middle future), for two scenarios (RCP4.5 and RCP8.5) regarding the 30-year period of the HIST simulation (1971 - 2000). Figure is showing only values that are outside the interval [-CI, +CI].

For both scenarios (RCP4.5 and RCP8.5), SST anomalies are positive and homogeneous in space (Fig. 4.2), i.e. SST is expected to consistently rise over the entire basin. In the near future (2011 – 2040), expected SST increase is similar for both scenarios, with an average increase between 0.6 °C and 0.8 °C. In the period of the mid-future (2041 – 2070), SST anomalies are more expressed in the RCP8.5 scenario, which is representing the worst case scenario (so-called "business-as-usual" scenario that is presuming momentary increase of the GHG). The expected increase of SST in the mid-future (2041 – 2070) is expected between 1.1 °C and 1.3 °C for the RC4.5, and between 1.6 °C and 2.0 °C for the RCP8.5.

ADRIATIC SEA SURFACE SALINITY

Averaged spatial SSS[2] distribution for the period 1971 - 2000 of the HIST simulation is also successfully reproducing basic properties of the Adriatic Sea (Fig. 4.3), with minimum salinity found in the coastal area that are under the influence of the local rivers (Bojana, Neretva, and northern Adriatic rivers of which the largest is River Po), and maximum in central parts of the Middle and Southern Adriatic (Artegiani et al., 1997a; Lipizer et al., 2014).

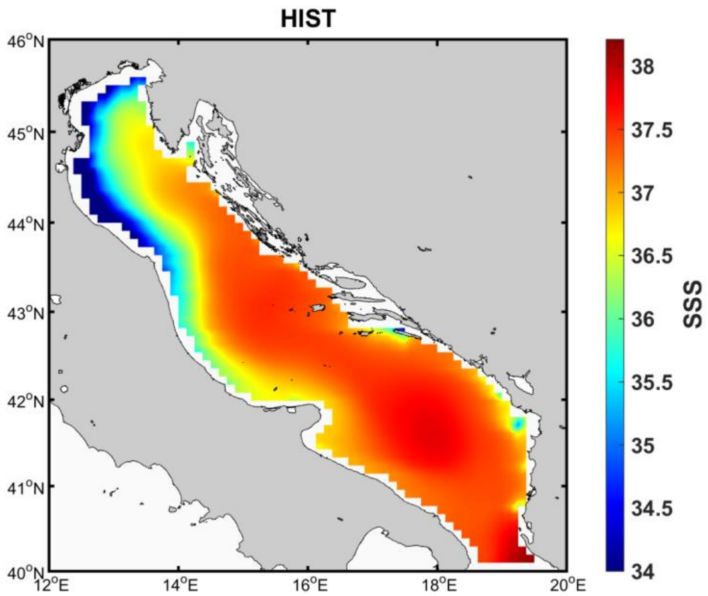

Figure 4.3 Sea Surface Salinity for the Adriatic Sea averaged over the 1971 - 2000 period of the historical simulation.

[2] SSS is measured in unit of PSU (Practical Salinity Unit), which is a unit based on the properties of sea water conductivity. It is equivalent to g/kg.

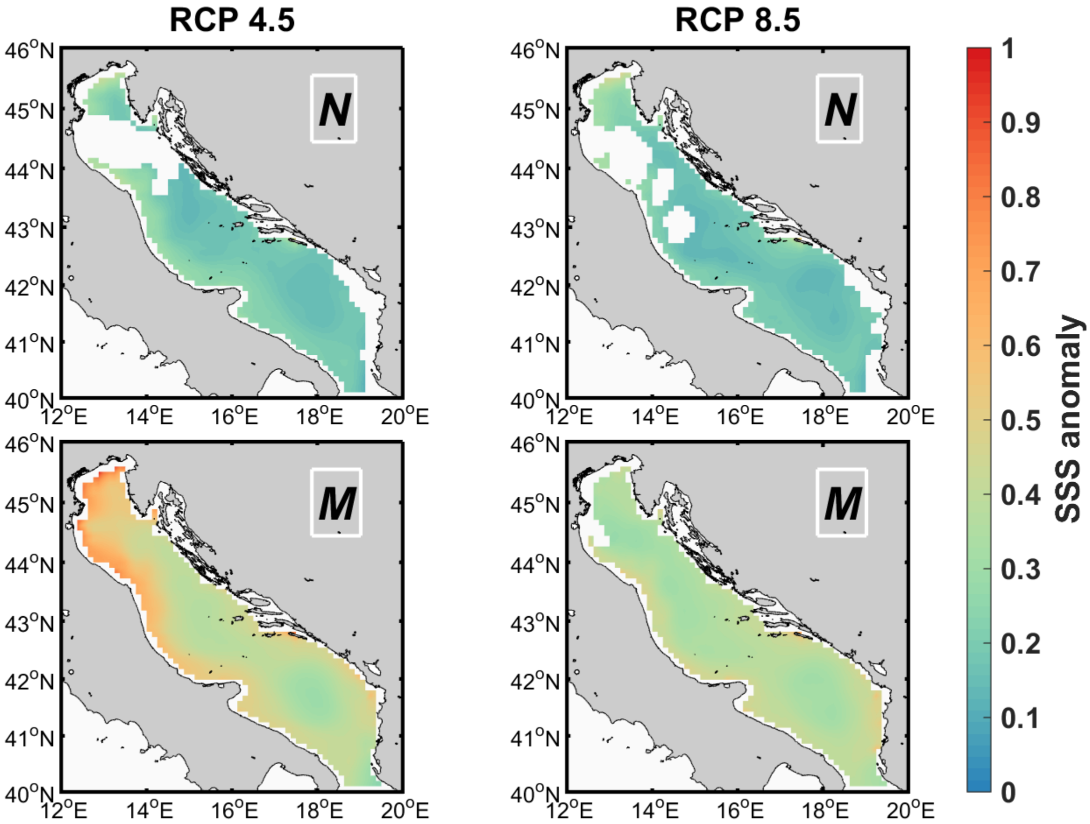

Figure 4.4 Sea Surface Salinity anomalies for the two defined periods (N - near future, M- middle future), for two scenarios (RCP4.5 and RCP8.5) regarding the 30-year period of the HIST simulation (1971 - 2000). Figure is showing only values that are outside the interval [-CI, +CI].

In the future, Adriatic SSS is expected to gradually increase in both, RCP4.5 and RCP8.5 scenario, with higher increase in coastal areas that are majorly influenced by the local rivers (Artegiani et al., 1997a, Fig. 4.4). In the near future (2011 - 2040), the SSS anomaly on average is 0.2. In the next period (2041 - 2070), RCP4.5 is showing higher SSS increase, especially in the coastal areas, of which the highest SSS increase is found in the northern and western coastal parts (up to 1.0). This can be an indicator of a future river discharge decrease, especially of northern Adriatic rivers and Po. RCP8.5 scenario for the same period is showing lower increase compared to RCP4.5, up to 0.7.

ADRIATIC SEA SURFACE HEIGHT

Averaged spatial SSH distribution for the period 1971 - 2000 of the HIST simulation, in accordance to previous studies (Orlić et al., 1992; Artegiani et al., 1997b), is revealing general cyclonic circulation over the entire basin (minimum SSH in central parts, and maximum SSH near the both coasts), interconnected with Southern and Middle Adriatic gyres.

In the near future (2011 - 2040), in both scenarios is expected a slight decrease in SSH over the whole Adriatic, after which the sea level will start to modestly increase (Fig. 4.6). Even though the global sea level is expected to rise (IPCC, 2019), this SSH stability of the Adriatic Sea could be a consequence of a possible increment of the dry periods over the Adriatic area (Meteorological and Hydrological Service of Croatia, 2009), thus resulting in higher evaporation and lower sea level.

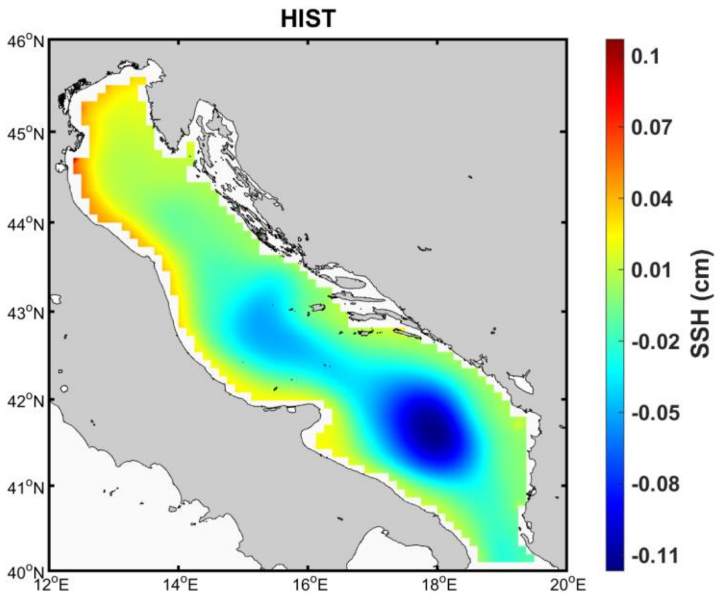

Figure 4.5 Sea Surface Height for the Adriatic Sea averaged over the 1971 - 2000 period of the historical simulation.

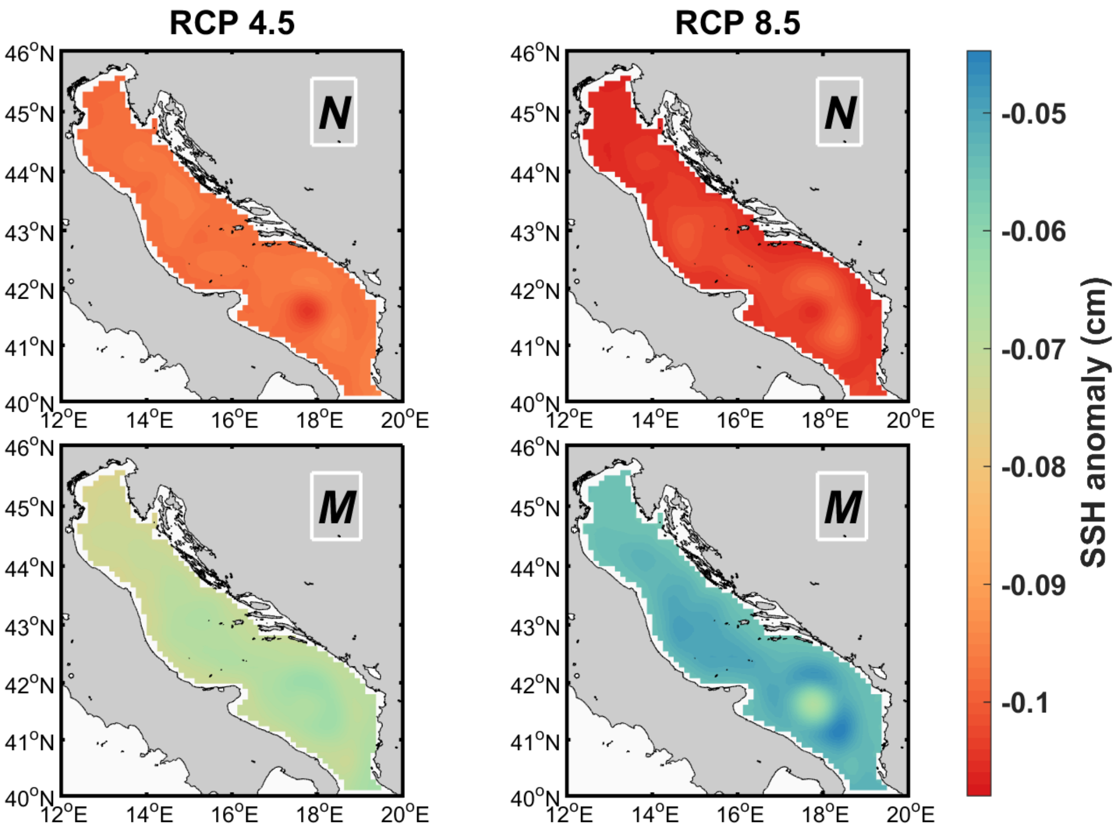

Figure 4.6 Sea Surface Height anomalies for the two defined periods (N - near future, M- middle future), for two scenarios (RCP4.5 and RCP8.5) regarding the 30-year period of the HIST simulation (1971 - 2000). Figure is showing only values that are outside the interval [-CI, +CI].

Recommendations for the RCM development

This section is addressing the last element planned by the AF of the RESPONSe project for this deliverable, i.e. "*Suggestions for further development of RCMs will be given.*"

The 12.5 km resolution RCMs analysed in this deliverable are based on the use of set (i.e. ensemble) of simulations recently developed and applied by several European scientific and research groups working together through EURO-CORDEX (https://www.euro-cordex.net/) and Med-CORDEX (https://www.medcordex.eu/) initiatives. Additional efforts are being made to develop coupled regional ocean and atmospheric (or coupled climate) models as well as climate models at spatial resolutions of 1 to 4 km. We expect in the next 3 to 5 years the possibility of access to the first sets of RCMs at high spatial resolution. For example, in recent activities called *CORDEX FPS Convection* (https://www.hymex.org/cordexfps-convection/wiki/doku.php), participating group from DHMZ is applying new version of the RCM RegCM at the resolution 4 km. At these spatial resolutions of 1 to 4 km, fine structures in coastal areas such as the larger islands are present, increasing the realism in the model setup and its results. Other *CORDEX FPS* projects address issues of the coupled regional climate models, the impacts of the aerosols on the European and Mediterranean regions, the interactions between the urban areas and climate, and interactions between the land-use changes and the climate system (https://cordex.org/experiment-guidelines/flagship-pilot-studies/endorsed-cordex-flagship-pilote-studies/). These various activities being developed through the *CORDEX FPS* work are currently done at the research level, but are preparing the way for the future applied studies over specific regions, including the Adriatic. Special attention is needed in evaluating and analysing available and future coupled atmosphere-ocean/sea regional climate models, where the use of the ensemble of simulations of the SST, SSS and SSH fields is required. This would address e.g., rather small climate change signal of the SSH as simulated by only one model used in this deliverable.

Majority of results presented in this deliverable are based on the moderate RCP4.5 and extreme (and low probability) RCP8.5 scenario. However, scenario of greenhouse gas concentrations under whose assumption it is possible to keep global warming below 1.5 ° C, so-called scenario RCP2.6 is needed to be addressed more actively in future work. In this case the matrix which is a combination of RCM and GCM models would not be filled in for all combinations since the use of this scenario is less often applied (but increasing). Regardless of this, we would be able to provide climate estimates changes in variables of interest over the Adriatic region in the case of aggressive reductions in global greenhouse gas emissions. Finally, a new generation of the scenarios linking more consistently the socio-economic assumptions and associated greenhouse gases emissions, so called SSP-RCP scenarios (e.g., https://climatescenario.org/primer/mitigation), are being applied more widely through the climate modelling and climate change impacts research communities.

In the D3.2.3 we will present the systematic errors of the regional climate models analysed in this deliverable, i.e. D3.2.1. While the model development (increasing the horizontal and vertical resolution, developing more comprehensive model modules/parameterizations, and increasing the consistency in the model assumptions), is the core approach for reducing the limitations in the regional climate models, various statistical approaches in the post-processing stage can be applied. Their aim is twofold: to describe the models errors with respect to selected observational dataset and to adjust the model raw output in order to increase its applicability in the climate impacts studies. Commonly, such methods of the statistical post-processing keep the original trends in the simulated climate fields (most commonly near-surface air temperature and total precipitation amount) but adjust these same fields in term of the mean model climate. Future work on the RCM development should be done with these statistical bias correction/adjustment methods, but extended also to a larger set of the climate variables.

Acknowledgments

We acknowledge the World Climate Research Programme's Working Group on Regional Climate and Working Group on Coupled Modelling, the former coordinating body of CORDEX, and the responsible panel for CMIP5. The simulations used in this work were also downloaded from the Med-CORDEX database. We want to acknowledge the climate modelling groups for producing and making available their model output.

We also acknowledge the Earth System Grid Federation infrastructure, an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling, and other partners in the Global Organisation for Earth System Science Portals (GOESSP).

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