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MILESTONES 4.3.5: Mediterranean extremes in RCM scenario runs summarised

Panagiotis Maheras (scientific responsible), Konstantia Tolika, Effie Kostopoulou, Christina Anagnostopoulou, Helena Flocas, Maria Hatzaki, Ioannis Tegoulias and Eftychia Rousi.

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<tr>
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<tr>
<td>PU Public</td>
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<td>PP Restricted to other programme participants (including the Commission Services)</td>
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<td>CO Confidential, only for members of the Consortium (including the Commission Services)</td>
</tr>
</tbody>
</table>
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>3</td>
</tr>
<tr>
<td>Description of Regional Climate Models used</td>
<td>5</td>
</tr>
<tr>
<td>Evaluation of Regional Climate Models</td>
<td>6</td>
</tr>
<tr>
<td>Spatial analysis of Climate extreme Indices for reference and future periods</td>
<td>11</td>
</tr>
<tr>
<td>Maximum and minimum values of Indices</td>
<td>15</td>
</tr>
<tr>
<td>Trend Analysis of Climate Indices</td>
<td>19</td>
</tr>
<tr>
<td>Relationship of Indices with Large Scale Circulation</td>
<td>23</td>
</tr>
<tr>
<td>Conclusions</td>
<td>30</td>
</tr>
<tr>
<td>References</td>
<td>32</td>
</tr>
<tr>
<td>Appendix A: Differences between model – observed data</td>
<td></td>
</tr>
<tr>
<td>Appendix B: Extreme Climate Indices</td>
<td></td>
</tr>
<tr>
<td>Appendix C: Maximum and minimum values of Indices</td>
<td></td>
</tr>
<tr>
<td>Appendix D: Trend Analysis of Extreme Climate Indices</td>
<td></td>
</tr>
<tr>
<td>Appendix E: Relationship of Indices with large scale circulation</td>
<td></td>
</tr>
</tbody>
</table>
1. Introduction

The Mediterranean basin is an area of great interest from climatological point of view as it combines a variety of geographical components (Figure 1) which in association with several synoptic circulation schemes present a number of local weather patterns. Although, the Mediterranean environs define a specific climate regime, the interactions among climate forcing factors, such as complex topography, lakes and land-sea contrast, result in gradual intra-regional variations in the climate of the surrounding lands. Hence, in areas toward the coast the climate shows maritime characteristics, while areas of high altitude adjacent to locations with Mediterranean climates, such as the plateaus of central Spain or the mountainous Pindos zone of western continental Greece, demonstrate typical characteristics of a continental climate.

**Figure 1.** Topographic map of the Mediterranean basin

The Mediterranean region is vulnerable to climate change particularly due to its sensitivity to drought and rising temperatures. Climate change is related with changes in the frequency and intensity of extreme climate events, which may adversely affect vital economic sectors, such as agriculture and tourism, and have substantive impacts on local communities. In addition, extreme climate events can be destructive to human health and well-being, while climate change may also have a direct impact on local people’s lives as it affects sectors such as water resources and energy. For all these reasons, in recent years the scientific community has developed a special interest in studying climate changes as described by changes in the occurrence and severity of extreme climate events.
Climate change is being a priority within the European Community's Framework Programmes for Research and within the Sixth Research Framework Programme emphasis was put on integrated research to address the functioning of the climate system. Funded by the European Commission and coordinated by the Meteorological Office Hadley Centre, the ENSEMBLES project aims to quantify the uncertainty in long-term predictions of climate change. Particular emphasis is placed to probable future climate changes in extremes, including heatwaves, storms, intense rainfall and drought. To focus on the needs of policymakers, ENSEMBLES considers impacts on timeframes ranging from seasonal to decadal to centennial, and at local, regional and global spatial scales. Some of the achievements of the project so far include the development of several Regional Climate Models (RCM), as well as a gridded observational dataset of temperature and precipitation for Europe, at 25km and 50km horizontal resolutions.

The main scope of this report is to use three ENSEMBLES RCMs in order to study the occurrence of specific climate extremes in the Mediterranean region. The domain of study extends from 12.5°W to 37.5°E and from 30 to 45°N. The RCMs are first evaluated against observations for the control period 1961-1990, then seven extreme climate indices are calculated (Table 1) and finally their trends are analysed over the entire time period, which is the 1961-2050 for the two models and the 1961-2100 for the third model. All analyses have been performed on seasonal basis, and generated a large number of plots. It is not feasible to incorporate all plots within the text of the report, and thus a few representatives are only presented and discussed. However, all figures are included in Appendices A to D at the end of the report.

**Table 1:** Climate extreme indices studied for the Mediterranean region.

<table>
<thead>
<tr>
<th>Index</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>TXQ90</td>
<td>Days with Tmax &gt; 90th percentile of daily Tmax of the base period</td>
</tr>
<tr>
<td>TNQ10</td>
<td>Days with Tmin &lt; 10th percentile of daily Tmin of the base period</td>
</tr>
<tr>
<td>FD</td>
<td>Total number of frost days (days with absolute Tmin &lt; 0°C)</td>
</tr>
<tr>
<td>HWD</td>
<td>Heatwave duration index (intervals (&gt;5 days) with Tmax&gt;5°C above the daily Tmax normal of the base period</td>
</tr>
<tr>
<td>PQ95</td>
<td>95th percentile of wet day amounts</td>
</tr>
<tr>
<td>PX5D</td>
<td>Maximum 5-day precipitation total</td>
</tr>
<tr>
<td>CDD</td>
<td>Maximum number of consecutive dry days (rainfall &lt; 1mm)</td>
</tr>
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2. Description of Regional Climate Models used

The ENSEMBLES Project has as priority to develop high resolution regional climate models along with high quality gridded climate datasets for Europe. It should be noted that by the time the analyses for this report started, three regional models were available and their data were utilised in our calculations. We used two IPCC emission scenarios, SRES A2 and A1B (Nakicenovic et al., 2000), in three regional climate models at 25km horizontal resolution, developed in three institutes and driven by two global ocean-atmosphere coupled models.

The first model (C4IRCA3) is provided by the Community Climate Change Consortium for Ireland (C4I). This is based on IPCC SRES A2 and the RCMs simulations are driven by ECHAM5, the 5th generation of the ECHAM General Circulation Model (GCM) developed at the Max Planck Institute for Meteorology in Hamburg. The regional climate model data consist of results from RCA3, which comprises the third version of the Rossby Centre Atmospheric model (Kjellström et al., 2005). The second RCM used is the ALADIN-Climate which is based on SRES A1B scenario. This model has been developed at Météo-France/CNRM (Centre National de Recherches Météorologiques) and it is described in Déqué and Somot (2007) and Radu et al. (2008). Its physical parameterisation (Déqué, 2007) is common with the GCM ARPEGE-Climate commonly used in a coupled mode for IPCC exercise or in an atmosphere stretched-grid mode for regional climate modelling. The future climate simulations for both models are available till 2050. Longer projections for a 150-year time span (1950-2100) are provided by the third model used in this report, delivered by the Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut, widely known as KNMI). The KNMI regional climate model RACMO2 (Lenderink et al., 2003; van den Hurk et al., 2006) is forced with output from a transient run conducted with the ECHAM5 GCM under the condition of the SRES-A1B greenhouse gas emission scenario. Table 2, summarises the RCMs used in the current study.

Table 2: Transient experiments 1951-2050 or 1951-2100 driven by global experiments

<table>
<thead>
<tr>
<th>Institute</th>
<th>Scenario</th>
<th>Driving GCM</th>
<th>RCM</th>
<th>Resolution</th>
<th>Acronym</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>C4I</td>
<td>A2</td>
<td>ECHAM5</td>
<td>RCA3</td>
<td>25km</td>
<td>C4IRCA3</td>
<td>1951-2050</td>
</tr>
<tr>
<td>CNRM</td>
<td>A1B</td>
<td>ARPEGE</td>
<td>ALADIN</td>
<td>25km</td>
<td>CNRM-RM4.5</td>
<td>1951-2050</td>
</tr>
<tr>
<td>KNMI</td>
<td>A1B</td>
<td>ECHAM5</td>
<td>RACMO</td>
<td>25km</td>
<td>KNMI-RACMO2</td>
<td>1951-2100</td>
</tr>
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3. Evaluation of Regional Climate Models

3.1 ENSEMBLES-RT5 daily gridded observational datasets

Gridded observational datasets of daily precipitation and temperature have been developed on the basis of a European network of high quality station series (http://eca.knmi.nl). The datasets cover the period 1950-2006. The datasets are available on 0.25 and 0.5 degree regular latitude/longitude grid, as well as on 0.22 and 0.44 degree rotated pole grid. The regular grid resembles the Climatic Research Unit monthly datasets grid for the globe. The rotated grid corresponds to the grid used in most ENSEMBLES Regional Climate Models (Haylock et al., 2008).

Temperature and precipitation data for the 1961-1990 period were extracted from the gridded observational datasets, for the domain of study (12.5°W - 37.5°E and 30°N - 45°N). The spatial and temporal availability of observational data vary among grids and variables. In the current study, only grids with 80% temporal coverage of data for the reference period were utilised. Figures 2a and 2b illustrate the grids used for the evaluation of temperature and precipitation indices respectively.

![Figure 2](image_url)

**Figure 2.** Grids with 80% temporal coverage of temperature (a) and precipitation (b) data for the 1961-1990 reference period.
3.2 Differences between model – observed data

Prior to discussing the climate extreme indices as derived by the three ENSEMBLES RCMs, the models were evaluated against the gridded observational temperature and precipitation datasets. The comparison employs each model output value to a corresponding observation grid cell. Regarding CNRM and KNMI, the model grid-points data are mapped on the exact observational grid. In contrast, the grid cells of C4I and the observational grid do not match up exactly, and hence comparison is done between model output and the nearest grid point value from the observed grid. To assess the accuracy of the models, differences between model and observations were calculated for the reference period 1961-1990. The differences refer to the climate indices presented in this report, in order to provide a more robust approach of the models ability to reproduce extremes.

**TXQ90**: All models tend to underestimate the TXQ90 index across the Mediterranean basin (negative differences). The index presents variant behaviour during summer months. In regions of high altitude it is usually underestimated, whereas in low altitude and coastal areas the index is overestimated. As can be seen in Figure 3, CNRM and KNMI present reverse behaviour. According to CNRM, extreme temperatures are highly underestimated in the eastern Mediterranean, with differences that in some cases reach -6°C, such as in the west of the Balkan Peninsula, whereas positive differences are observed (overestimation) to the west of the Iberian Peninsula (Portugal). In contrast, the KNMI model underestimates the index in the Iberian Peninsula while in the central and eastern part of the study region (especially in Italy and Greece), the model simulates better the index as reveals small differences with the observational gridded data.

**Figure 3.** Differences of TXQ90 between CNRM (left), KNMI (right) and gridded observations, for summer.
TNQ10: The evaluation of the three examined models results, showed that in most cases the TNQ10 index is underestimated, with negative differences covering the largest part of the study area. Among the three models, KNMI is the one presenting the smallest differences in all seasons, while CNRM shows large negative biases (winter, spring and autumn). Regarding C4I, the winter spring and autumn difference patterns are quite similar, showing positive differences in the Balkans which are more pronounced in winter. In contrast, during summer, the index is underestimated by this model (Figure 4).

**Figure 4.** Seasonal differences of TNQ10 between C4I and gridded observations.

**FD:** Large positive differences are observed for the CNRM model, along the study region, which tends to overestimate the number of frost days especially in winter (Figure 5, middle plot). For the other two seasons (spring and autumn) positive differences are found, mainly in the eastern Mediterranean. The remaining models present similar patterns in all seasons, underestimating the index (negative differences). As expected, the highest underestimations are found in winter mainly in high altitude regions (Figure 5, left and right plots).
Figure 5. Winter differences of FD between models and gridded observations.

**HWD**: The HWD index is rather well simulated by all models, as differences between models and observed data range between ± 2 days. All models present minimum differences (almost zero) in extended parts of the Mediterranean during summer. More specifically, C4I simulates the index well in the central Balkan Peninsula, CNRM in western Iberia, in central Balkans and in southern Turkey and the KNMI model in western Iberian, southern Balkans and coastal parts of Turkey. In spring, the examined RCMs tend to underestimate the index values in the Iberian Peninsula and eastern parts of Turkey. The results for autumn are in overall agreement with those of spring, but in this case differences are smaller.

**PQ95**: Overall, the underestimation of PQ95 is more pronounced by CNRM compared to the other models. However, all three models reveal wetter conditions along the western coast of the Balkan Peninsula in winter (Figure 6). Such wet conditions are also found in spring and autumn at the mountainous western part of the Balkans. In addition, all models agree and present drier conditions (underestimation of the index) over Turkey.

Figure 6. Winter differences of PQ95 between models and gridded observations.
**PX5D:** In this case, all models overestimate PX5D in large parts of the study region. Particularly, C4I and KNMI present similar patterns in winter spring and autumn with increased values for the index, in several scattered sub-regions over the Iberian Peninsula and the western coast of the Balkan Peninsula (Figure 7). Note that CNRM shows drier conditions compared to the other two models. However, it is noteworthy that CNRM defines positive differences over large parts of the Balkan Peninsula, especially as far as spring and summer are concerned.

![Figure 7. Winter differences of PX5D between models and gridded observations.](image)

**CDD:** CNRM provides better simulation of winter and autumn values of this index compared to the other two models. Overall, CDD is underestimated in the majority of the study region (negative differences). However, it should be highlighted that regarding summer, the KNMI model displays reverse behaviour with large positive differences (overestimation) especially in the entire Italian and Balkan Peninsula, as well as in the northern part of Turkey (Figure 8).

![Figure 8. Summer differences of CDD between models and gridded observations.](image)
4. Spatial analysis of Climate extreme Indices for reference and future periods

**TXQ90**: The 30-year means of the extreme maximum temperatures show that Mediterranean will get warmer in the future, especially during the period 2071-2100 (according to KNMI). All models agree that the highest values of the TXQ90 index will appear mainly in the southern part of the Iberian Peninsula. It is worth emphasising that KNMI expects the heat to get worse by the end of the 21st century for summer, and estimates that the majority of the study region will frequently experience temperatures of up to or greater than 40 degrees Celsius (Figure 9).

![TXQ90 Summer 2021-2050 (KNMI)](image1)

**TNQ10**: Analogous results are found for the means of the TNQ10 index in the Mediterranean basin. The extreme minimum temperatures seem to increase in the future, with the most intense warm conditions occurring during the second future period (2071-2100, KNMI). The largest increases of the TNQ10 index values are detected once again in the western part of the study area, especially in southern Iberia and Portugal. Regarding the winter TNQ10 pattern over the Balkan sub-region, it should be mentioned that the C4I model future projections (2021-2050) resemble the projections of KNMI for the end of the 21st century.

**FD**: Focusing on winter mean values of the FD index (Figure 10), it is found that there will be a decrease of frost days in the Mediterranean, which is expected to be more
evident in the central and western part of the domain of study. CNRM is found to be the “coldest” of the three models (note the large number of FD in reference period); estimating that even in the future period 2021-2050, the Balkan Peninsula and the Turkey region will be characterized by a large number of frost days. In these areas the index value reaches the number of about 80 days.

**Figure 10.** Number of frost days (FD) in winter as estimated by all models for the reference and future periods.

**HWD:** A significant increase of this index is simulated by the three models for the future periods for all seasons. In contrast to the previously discussed temperature indices, the future HWD spatial patterns differ from model to model, especially for the winter period. Specifically for the 2021-2050 period, KNMI estimates that there will be almost no change in the index values (apart from some sea areas), while the other two models show an increase of the winter HWD index in the whole Mediterranean. As concerns summer heatwaves, it should be highlighted that the future projections of the CNRM model for the years 2021-2050, resemble those of KNMI for the end of the 21st century. This was also observed in the future projections of the two models for TNQ10.
**PQ95**: With respect to extreme precipitation heights, it seems that the three models agree on the spatial distribution of the index values, for winter spring and summer. Specifically, extreme winter precipitation conditions are mainly found on the western part of the Iberian Peninsula, in Marseille (France), in the western coasts of the Balkans and Greece and in southern Turkey. Future climate projections do not show changes in the precipitation patterns, however the extreme rainfall seem to become more intense in the last 30 years of the 21st century (Figure 11). The results obtained by the three models differ from each other as regards autumn extreme precipitation amounts. In particular, KNMI appears “wetter” with large values of the index covering major part of the domain of study. It is estimated that extreme rainfall conditions will become more intense in future. For instance, as far as the period 2071-2100 is concerned, values of the index exceeding 30mm appear almost across the entire Mediterranean basin. Exceptionally high rainfall rates are estimated by C4I at the western parts of the Iberian, Italian and Balkan Peninsulas. Finally, according to CNRM regions with high extreme rainfall amounts are expected mainly in northern Italy and the western Balkans.

![Figure 11. Winter PQ95 as estimated by all models for the reference and future periods.](image)
**PX5D**: Regarding the PX5D index, all three models agree that no exceptional changes are expected either in the spatial distribution or in the magnitudes of the index. The models indicate that sub-regions with the highest index values generally are western Iberia, southern France, western Balkans and the southern part of Turkey. The latter comes in accordance with the previous index. For summer, the most notable effect of this index is derived by KNMI which reveals higher values (for both the reference and future periods) than those of the other two models, especially in the northern part of the study area.

**CDD**: A general swift to drier conditions is predicted by all models under consideration. The values of the CDD index increase from north to south and this pattern appears almost identical in the future periods. In the case of winter, it could be mentioned that the CNRM model is the “driest” among the three. The projected values of the index for the period 2021-2050 are in some sub-regions, such as central, southern Iberian and eastern Balkan Peninsulas, even higher that the ones estimated by the KNMI model, for the end of the 21st century (2071-2100). For summer, KNMI presents the longest maximum dry spells. According to this model, it seems that in the future, the southern Iberian Peninsula and Greece will be characterised by a persisting absence of rainfall, since the length of the dry spells approaches 90 days (Figure 12).

**Figure 12.** Consecutive dry days (CDD) in summer as estimated by KNMI for the future periods 2021-2050 (left) and 2071-2100 (right).
5. **Maximum and minimum values of Indices**

The utmost extreme values of the previous set of indices were explored to identify regions that climate extremes are observed in the present, and provide estimation of where such events tend to occur in the future. Monitoring the extreme (maximum or minimum) values of the indices will assist to address questions such as: what is the spatial distribution of extreme events, and suggest some measure of persistence over certain regions. To reach this aim, the study region has been split into three main latitudinal zones, each having a width of 5-degrees in latitude, and subsequently the five (5) grid points showing the most extreme values for each index were detected. The analysis was made for the reference (1961-1990) as well as the two future periods (2021-2050) and (2071-2100) for all three models. The southern latitudinal zone extends from 30° N to 35° N, the second from 35° N to 40° N, and the third spans between 40° N and 45° N. Similarly, this exercise was repeated by splitting the region in five equidistant longitudinal bands, each of about 10 degrees in longitude (12.5° W - 2.5° W, 2.5° W - 7.5° E, 7.5° E - 17.5° E, 17.5° E - 27.5° E and 27.5° E - 37.5° E). This attempt was made to determine grids where the indices present their extreme values and consequently to determine whether such extremes occur at the same locations in future time periods. For most indices the absolute maximum values were used, apart from the TNQ10 index, for which its absolute minimum values were sought at each sub-domain.

It is noteworthy that the models analysed revealed some sort of “persistence” regarding regions where the extreme values of each index are found. This means that the same regions illustrating the maximum (minimum) values for an index in the reference period, also present the future maximum (minimum) values. For instance, regarding the 1961-1990 period, the KNMI model defines the winter maximum values for PQ95 along the western coast of Israel for the southern latitudinal zone, at the southern coast of Turkey for the middle zone and the western coast of Iberian Peninsula for the upper latitudinal zone. The model provides similar results with respect to the two future periods. In general, the results of all three models are in good agreement, as far as the locations of the extreme indices values are concerned.

**TXQ90:** The extremes of the TXQ90 index seem to occur in the lower part of each 5-degrees zone of latitude, except for summer when grids with extremes scattered over the study region (Figure, 13). In summer, the three models agree and the maximum values of TXQ90 are marked in close proximity. Namely, areas showing high TXQ90 values are northern Africa, northern Greece, central Spain, Syria and Turkey. Regarding the extreme
values of the index per longitudinal zones, it is characteristic as well as rather expected, that the southern parts of the study sub-zones are those presenting the greatest values of extreme maximum temperatures. Note that the results are comparable among models and seasons.

**Figure 13.** The five maximum values of TXQ90 per 5-degrees zones in latitude for the reference and future periods (1961-1990 and 2021-2050 respectively).

**TNQ10:** It should be highlighted that the utmost minimum values were explored as regards the TNQ10 index. In this case the results are in complete agreement for all seasons, for the present and the future periods and for all models. The analysis of extremes by latitudinal zone, has distinguished three regions: Morocco, southern France and eastern Turkey (Figure 14). According to the longitudinal splitting of the region, extreme index values are also observed in the Dalmatian coast and in northern Greece.
Figure 14. As Figure 13 except for TNQ10.

FD: Equally to TNQ10, great similarity is found for FD among seasons, study periods and models, especially regarding the analysis of results within latitudinal zones. The regions with extreme index values are Morocco, southern France and southeastern Turkey.

HWD: A scatter of grids with extremes exhibits limited spatial coherence of the results for the HWD index by all models. Therefore, it is not appropriate to draw conclusions for the extreme behaviour of the index over the Mediterranean in the future.

PQ95 & PX5D: The extreme values of these two indices seem to display relatively similar spatial distribution. In all seasons, except for summer, the extreme index values are observed in the same areas for both reference and future periods (Figure 15). These maxima are found in northern Portugal, northern Morocco and southern Turkey. It should be highlighted that in the case of summer, although the results present the same pattern for the reference and the first future period (2021-2050), with respect to the last 30 years of the 21st century, the estimations of KNMI show that the extreme values of both indices are in different
locations. Specifically, the grids showing the maxima are gathered solely in the western Mediterranean, whereas are completely missing from the eastern parts of the basin.

Figure 15. The five maximum values for winter and autumn PQ95 and PX5D per 5-degrees zones in latitude for the reference and future periods.

**CDD:** In winter and spring there is spatial inconsistency among the models results with the longest dry periods mainly detected in the lower part of each latitudinal band for all periods and models. The results differentiate in summer and especially in autumn, when the extreme values of the CDD are observed in the easternmost parts of the study area. The analysis of the various longitudinal sub-regions show that the extreme values of the index are found in low latitudes (i.e. Africa) as it was expected. It should be underlined that in summer, and particularly for the later future period (2071-2100), the extreme values of the index, as defined by KNMI, shift northwards and occur in coastal regions (Sardinia, Crete and Cyprus) in the central part of the Mediterranean (Figure 16).
Figure 16. The five maximum values for summer CDD per 5-degrees zones in latitude for the reference and future periods.

6. Trend analysis of Climate Indices

Possible trends of the indices were calculated with the Kendall-tau test employed to estimate their statistical significance. Maps were constructed for each index, indicating grids with trends significant at the 0.05 level of significance. Red colours were chosen to represent positive (increasing) and blue negative (decreasing) trends.

TXQ90: Generally positive trends of TXQ90 are seen in the Mediterranean. The highest positive trends are found over an extended region, especially for summer, particularly by CNRM and KNMI (Figure 17). In many cases the positive trends exceed the 0.5°C per decade. With respect to CNRM, the highest trends are detected in the eastern Mediterranean in all seasons. In contrast, C4I reveals the highest trend in the western Mediterranean. KNMI shows higher, than the other two models, trends. This is not surprising, owing to the longer time period of this scenario (until 2100), as the greatest changes are expected by the end of the 21st century. Concluding, all three models show the lowest trends for TXQ90 in winter, of approximately 0.25°C per decade. In particular, the highest winter TXQ90 trends as estimated by KNMI appear in the eastern Mediterranean, while in the two intermediate seasons high trends are also found in the western parts.
**Figure 17.** Statistically significant trends of TXQ90 for summer as estimated by the three examined models (trends are statistically significant at 0.05 level of significance).

**TNQ10:** Generally all models show positive trends, with the highest increasing trends during summer (0.4-0.5°C/decade). Note that the lowest values of positive trends are observed for spring by all models (0.25°C/decade). Trends estimated by C4I differentiate from the other two models. In all seasons low trends are observed in many regions and especially in spring only few statistically significant trends are found (Figure 18). Notable feature of this index is that both CNRM and KNMI patterns reveal the maximum of the positive trends in the eastern Mediterranean for all seasons (Figure 18).

**Figure 18.** Statistically significant trends of TNQ10 for winter and spring for the three models (trends are statistically significant at 0.05 level of significance).

**FD:** Contrarily to the two previous indices, negative trends are observed in frost days. The highest negative trends are shown in winter (approximately -2 days/decade). For CNRM the highest decreasing trends appear in the western part of the Mediterranean basin, while in
contrast KNMI detects them in the Balkan Peninsula and generally the eastern part of the study area. CNRM presents similar trends, whereas C4I shows lowest trends, which might possible be attributed to the different emission scenario (SRES A2) used in this climate model.

**HWD**: In this case, lower trends are observed over the continent and higher over the sea. This may be caused due to the higher heat capacity of the sea with retains high temperatures for a longer time period. As expected, all models reveal the highest values of the HWD index during summer. In particular, C4I shows maximum trends in the western parts of the basin which is in agreement with the respective trends found for TXQ90. In CNRM, the summer maximum trends are observed over the Balkans and the overall eastern Mediterranean. Two summer maxima are captured by KNMI, the first is observed over the Iberian Peninsula and the second over Turkey. With respect to the remaining seasons, similar results are obtained by all models for all regions.

**PQ95**: Less spatial coherence describes the PQ95 trend results, as both positive and negative trends are observed. Moreover, fewer regions reveal statistically significant trends. Results vary among the three models. C4I generally shows weak climatic signal in all seasons. During winter, positive trends are seen over north and west parts of the Balkan Peninsula and Turkey but negative trends in Cyprus. The remaining seasons do not show any substantial trends. In CNRM the positive trends reveal higher values compared to the negative ones, which translates to an increase of the extreme rainfall conditions, particularly for winter in the western Iberia and for spring in northern Italy. For the other seasons scattered grid points with positive or negative trends are marked in the maps. KNMI presents higher trends (positive or negative) probably due to the longer data time series (until the end of the 21st century). The most notable feature of this analysis refers to the negative summer trends that cover large part of the study area, indicating that extreme precipitation tends to decrease during the warm part of the year by the end of the 21st century. In contrast this model shows that intense precipitation episodes should be more often expected in autumn (Figure 19).
Figure 19. Statistically significant trends of PQ95 for summer and autumn as estimated by KNMI for the 1951-2100 period (trends are statistically significant at 0.05 level of significance).

PX5D: Variant trends (positive and negative) are observed for all models and all seasons (no clear signal). C4I shows negative trends in western Mediterranean especially for winter and autumn. In contrast, CNRM presents positive trends in Iberia except summer. According to KNMI, in winter the positive trends are the northern part of Iberian Italian and Balkans Peninsulas. In spring and summer mostly negative trends are observed, while in autumn positive trends appear in the central Balkans and along the Adriatic Sea (Figure 20).

Figure 20. Statistically significant trends of PX5D as estimated by KNMI for all seasons for the 1951-2100 period (trends are statistically significant at 0.05 level of significance).
CDD: For the first two models large regions do not show statistical significant trends. It seems that spells of consecutive dry days will increase mainly during the last 30 years of the 21st century. According to KNMI the CDD index will increase generally all over the Mediterranean especially during spring and summer. This increase may reach the 2 days per decade. The spatial distribution of the trends during spring presents a north to south gradient (with the greatest values to the south), while during summer it is reversed, with the highest values to the north (especially Iberian Peninsula and Italy). The other two models reveal weaker climate signal probably due to the shorter data series. The results of these two models differentiate with each other as well as with the KNMI model. Spatial incoherence characterises their trend results. According to CNRM the highest positive trends of CDD (increasing drier conditions) appear during winter in the Balkan Peninsula and Greece and during summer at the northeastern part of the Mediterranean. Regarding C4I, the highest positive trends are evident over Iberia and southwestern Mediterranean (Africa) during winter and spring.

7. Relationship of Indices with Large Scale Circulation

7.1 Data-Methodology

The large scale atmospheric circulation greatly determines the occurrence of extreme events, and therefore, it is very important to explore the ability of the climatic models to represent this relationship. In the present study, the impact of the upper level large scale circulation on precipitation and temperature extremes over Mediterranean is examined using three regional climatic models, in an attempt to inter-compare these models in the present climate.

For this purpose, daily precipitation and temperature data from the three RCMs were employed for the period 1958-2006 with spatial resolution 0.25x0.25: CNRM-RM4 (RM4), C4IRCA3 (RCA3) and KNMI-RACMO2 (RACMO2). Also, 500 hPa geopotential height data were employed for the greater European region, as derived from the two parent GCMs ALADIN and ECHAM5 dataset for the same period. The ALADIN provides results for the period 1950-1999 on a 2.8x2.8 grid (approximately) and ECHAM5 for the period 1950-2000 on a 1.86x1.875 grid. The results of the three models are evaluated against the corresponding results derived from the gridded observational datasets daily precipitation and temperature over the examined area (Haylock et al., 2008) and the NCEP/NCAR geopotential height at
500 hPa for the same period (hereafter will be referred as “observed results”). The isobaric level of 500 hPa was selected, as representative of upper troposphere, where important dynamic factors, independently of the topography, control the temperature and precipitation regime at the surface.

The selected climatic indices that were employed are: the 90th percentile of maximum temperature (TXQ90), the 10th percentile of minimum temperature (TNQ10), the 95th precipitation percentile (PQ95) and the consecutive dry days (CDD). As was described in the previous sections, these indices were calculated on seasonal and annual basis for the present period over Mediterranean, separately for the three regional models.

The relationship between the large scale circulation and the climatic extremes was explored by applying the Regularised Canonical Correlation Analysis (RCCA), which allows the investigation of the linear relationship between two different fields and determines optimal pairs of concomitant spatial patterns that account for the maximum amount of variance within the two time series separately, and, at the same time, their optimally correlated time components. CCA has been widely used to investigate the impact of large scale circulation on the regional rainfall or temperature regime (Xoplaki et al., 2000; Dunkeloh and Jacobieit, 2003; Bartzokas et al., 2003; Wallace et al., 1992; Barnett and Preisendorfer, 1987). In general, CCA allows the investigation of the linear relationship between two different fields and determines optimal pairs of concomitant spatial patterns that account for the maximum amount of variance within the two time series separately, and, at the same time, their optimally correlated time components. Pairs of spatial patterns (canonical loadings) are derived from the two datasets, in such a way that the correlation of their time coefficients (canonical scores) is maximized, giving a measure of the degree of association between the two temporal patterns. The canonical scores, representing the intensity of the atmospheric circulation mode, are normalized to unity, so that the canonical correlation patterns represent the typical strength of the corresponding spatial patterns (Von Storch and Zwiers, 1999).

Here, the regularized extension of the CCA (RCCA) is applied to seek correlations between two data matrices X, Y when the number of columns (variables) exceeds the number of rows (observations). As the number of variables increases, greatest canonical correlations are nearly 1 because of recovering of canonical subspaces that do not provide any meaningful information. To deal with this problem a regularization step is included in the calculations by adding a regularization parameter \(\lambda_1, \lambda_2\) on the diagonal of each correlation matrix of X and
Y, respectively, and so allow the inversion (Leurgans et al., 1993). The calculations were performed with the aid of the statistical language R (Gonzalez et al., 2008).

The RCCA was applied (in R language) between each index dataset for each regional model and the 500hPa geopotential height of the corresponding parent GCM model: ALADIN for RM4 (CNRM) and ECHAM5 for RACMO2 (KNMI) and RCA3 (C4I). Thus, this method will allow a physical interpretation of the mechanisms controlling the regional climate variability of extremes.

7.2 Results

The first four canonical pairs (here, derived from the 500hPa geopotential height and each extreme index) for each season, for the three models and for observed data are presented in Appendix E. In these pairs, the canonical loadings are plotted. High loadings indicate that the corresponding variables (e.g. the data series of the corresponding grid points) are highly correlated with the canonical variate and thus, have more in common with it. The correlation between the successively extracted pairs of the canonical variates is an overall index of the canonical correlation between each two sets of variables and becomes smaller and smaller at successive pairs.

In general, the evaluation of the RCCA results has demonstrated that all three models compare better for temperature extremes rather for precipitation extremes, following the general finding of the regional model evaluation in section 3. Furthermore, CNRM provides more coherent results across the Mediterranean region, especially for temperature extremes and less for precipitation, as compared to the other two models. Although extreme values are not normally distributed, while the multivariate methods (such as RCCA) make assumptions of normality in the data, the RCCA results for the observational datasets do not appear inconsistencies between the two fields, contrary to the corresponding model results. These inconsistencies between general circulation patterns and the extremes patterns could be due to the possible inability of the models to capture their relationship or the coexistence of other thermodynamic factors. More specifically:
**Figure 21.** Spatial distribution of the canonical loadings for the first four canonical pairs of geopotential heights at 500 hPa (upper panels) and TXQ90 during summer (lower panels) for a) CNRM, b) C4I and c) KNMI model. Dashed contours indicate negative values. Contour intervals by 0.1.

**TXQ90:** The CNRM succeeds better to reproduce the observational patterns in all seasons, as compared to the other two models. The canonical loadings are stronger for KNMI and CNRM, as compared to C4I and more uniform across Mediterranean, especially during the transient seasons, autumn and spring (see Appendix E, Figures E4 and E8). During summer for CNRM, the general circulation seems to explain well the extreme maximum temperature patterns. In this season, C4I large scale patterns (see Figure 21b) are consistent with observational results, but not really consistent with the regional scale patterns while the canonical loadings of TXQ90 demonstrate spatial variations of different magnitude across the Mediterranean (see Figure 21b). In summer, for CNRM and KNMI the resultant pairs are quite similar. For instance, pair 1 (pair 2) in Figure 21a with pair 1 (with inverse sign) (pair 4) in Figure 21c. Specifically, for CNRM, increased geopotential height values lead to increased maximum temperatures over the whole Mediterranean region (Figure 21a, pair 1), while a blocking over southern and north-eastern Europe causes an increase over the main part of
Mediterranean (Figure 21a, pairs 2 and 4 respectively). During the other seasons, it seems that characteristic low-frequency patterns govern the patterns of maximum temperatures. For instance, for CNRM and KNMI in autumn (see Appendix E, Figure E8), the European blocking (Metaxas et al., 1993) (pair 1 and 3, respectively, the EA/WR (Krichak and Alpert, 2005) (pair 3 and 1, respectively) and the Scandinavian pattern (Barnston and Livezey, 1987) (pair 4 and 2, respectively) are associated with the warm extremes.

**TNQ10:** The evaluation suggests that the models present similar behaviour with the corresponding TXQ90 results, except that C4I appears better ability in spring and that the ability of all three models is limited in summer. In winter, CNRM compares very well with observations. Moreover, KNMI and CNRM produce more similar pairs, however, KNMI appears weak loadings at the 500 hPa geopotential field (Figure 22b). For instance, in Figure 22, the second (third) pair of CNRM is related to the third (second) of KNMI in the field of TNQ10. It should be noticed that in CNRM the patterns of minimum temperatures are more consistent with 500hPa circulation. In most cases for all models the European blocking is the most prominent pattern of atmospheric circulation, while the EA/WR pattern appears frequently.

**Figure 22.** As in Figure 21, but for TNQ10 during winter.
**PQ95:** The results for PQ95 are different among the three models, reflecting their low skill in simulating precipitation indices (as shown in previous sections). Furthermore, the sign of the loadings of the index vary spatially across Mediterranean, while the 500 hPa geopotential height loadings are rather weak for all three models, especially for KNMI, indicating the possible inability of the models and/or the method to capture the relationship between large scale circulation and precipitation extremes. Besides, precipitation correlates better with the lower than the upper troposphere circulation. Among the three models, the best resemblance with the observed results is evident for C4I, mainly in autumn and summer. A common winter pattern related to the PQ95 in the CNRM and C4I models is the Eastern Mediterranean Pattern (EMP) in winter (Hatzaki et al., 2007): pair 1 for CNRM (Figure 23a) and pair 2 for C4I, with inverse sign (Figure 23b). Also, in CNRM, the East Atlantic pattern (pair 2) and the Scandinavia pattern (pair 4), two dominant winter patterns affecting European region, are reflected.

![Figure 23](image_url)  
**Figure 23.** As in Figure 21, but for PQ95 during winter.
**CDD:** In winter, CNRM succeeds in reproducing the observed patterns with the same weight, verifying its ability during this season, similarly to the other indices. C4I is also capable to capture two pairs, while KNMI appears low loadings. As can be seen in Figure 24, prevailing large scale patterns in winter are the Eastern Mediterranean Pattern (EMP), appearing as a first pair in the observed and CNRM results (Figure 24a) and EA/WR pattern, forming the forth pair in the observed and CNRM (Figure 24a) and the first of C4I (Figure 24b). In summer, C4I is now able to reproduce the observed patterns (see Appendix, Figure E30b), contrary to the other two models. Moreover, C4I provides more consistent results between the two fields, as compared to the other two models, reflecting its better simulation ability of this index in summer. During the same season, KNMI and especially CNRM are related to very weak loadings, indicating the inability of the models and/or the method to capture the relationship between the large scale circulation and the extreme dry spells, although KNMI and C4I are driven by the same parent GCM. Persistent large scale circulation patterns are captured for C4I pairs, as the Scandinavian pattern (first pair) and an extended blocking over greater European region (third pair, with inverse signs, see Appendix E). The inconsistencies between general circulation and extreme dry spells that occur in

**Figure 24.** As in Figure 21, but for CDD and winter.
summer can be attributed to thermodynamic factors that cause local scale precipitation (Saaroni and Ziv, 2000; Ziv et al., 2004), being unresolved by the regional models, while the upper level circulation does not play significant role (Maheras et al., 2004).

The evaluation reveals that CNRM produces better results in winter, C4I in autumn, and KNMI in spring, as compared to the observations. For winter, autumn and spring, CNRM results compare well with C4I, revealing almost the same circulation patterns, as the Eastern Atlantic pattern, the European blocking, the Eastern Mediterranean Pattern, though the CDD spatial distribution is quite complicated. The loadings for KNMI are weak and no specific low-frequency pattern prevails.

8. Conclusions

Overall, the evaluation analysis of the models against the gridded observed data showed that all models underestimate extreme warm temperatures (TXQ90). The extreme cold temperatures (TNQ10) seemed to be better reproduced especially by KNMI. The ‘coldest’ model was found to be CNRM, particularly for low temperatures of the transitional seasons. These findings are further supported by the results for the number of frost days, where CNRM presents positive differences (i.e. more frost days) especially in the eastern part of the Mediterranean. In contrast, C4I was seen to simulate better the low temperatures for spring and autumn than in the other two seasons, while it also performed well in reproducing the HWD index. The models exhibit lower skill in simulating precipitation indices. However, PQ95 was reproduced better than PX5D, although most models show drier conditions, than those defined by the observational data. CNRM showed drier features, especially in the western Mediterranean for autumn compared to the other models. Despite the dry characteristics of models, they underestimate the CDD index. In this case CNRM seem to simulate better winter CDD than the other models. The most notable finding for this index refers to the exceptionally wet summer season that was estimated by KNMI especially for the eastern Mediterranean, which however requires further study.

To summarise the main results of the indices, bearing however in mind the discrepancies of the models in relation to the gridded observed data, all models marked a shift towards warmer climates, with the high temperatures (TXQ90) getting warmer in the future. According to KNMI the heat will get higher during the 2071-2100 period. These findings are in accordance with those for the HWD, as this index tends to increase in future summers. The models also indicated increase in summer low temperatures (TNQ10). In the remaining
seasons, the ‘cold’ CNRM (see evaluation discussion above) presented colder conditions both in present and future periods especially in the Balkan Peninsula. In contrast, KNMI estimated warmer conditions in the eastern Mediterranean. Additionally, KNMI and C4I present reduced number of frost days in spring and autumn, whereas CNRM predicts larger number of frost days in present and future periods. With respect to precipitation indices, the models present similar present and future spatial patterns as regards extremes precipitation amounts (PQ95) in winter, with the most extreme precipitation observed along the western boarders of all the peninsulas of northern Mediterranean. CNRM is found to be the drier among models, especially in spring and autumn. It is noteworthy that KNMI estimates wetter future autumns along the region. Moreover, it is worth to note that KNMI predicts larger dry periods (CDD) in the future, which seem to be more pronounced in the eastern part of the basin.

The trend analysis revealed large positive trends for both extreme high and low (TXQ90, TNQ10) temperatures especially by CNRM and KNMI. The latter shows intense trends in the eastern part of the domain. The trends seem to be getting larger in summer for both variables. The precipitation trends do not allow us to get a clear picture for the future behaviour of precipitation extremes. Nevertheless, all models showed some increasing trends in winter extreme precipitation amounts (PQ95) at the northern areas of the domain. Note that KNMI presented the most statistical significant trends. In addition, positive trends are found for winter in the number of consecutive dry days (CDD). C4I estimates lengthier dry spell to the west, CNRM to the east, while KNMI defines them in the southern half of the basin. The HWD index as estimated by CNRM showed large positive trends in the eastern Mediterranean. Moreover, frost days present negative trends in all seasons, especially by CNRM and KNMI.

The models appeared sensitive to define regions vulnerable to experience extremes in both present and future periods. In most cases the three models marked the same grids having the maximum (or minimum) values of indices. Models generally agreed regions showing extremes in present are the most vulnerable to experience extreme climate events in the future too.

The observed large scale upper tropospheric patterns related to climatic extremes in Mediterranean are not well reproduced by the models in all seasons while the model results are not always consistent between the two fields. According to the evaluation process, the CNRM is more capable in winter, C4I in summer and KNMI in transitional seasons. Moreover, the results, as produced by the three climatic models, appear differences and do not inter-compare well. All three models compare better and are better evaluated for their results.
concerning temperature extremes rather for precipitation extremes. The CNRM and KNMI exhibit more coherent patterns for TXQ90 in summer and TNQ10 in winter. The C4I provides more consistent results for CDD in summer, with high loadings.

References


**APPENDIX A:** Differences between model – observed data

**APPENDIX B:** Extreme Climate Indices

**APPENDIX C:** Maximum and minimum values of Indices

**APPENDIX D:** Trend Analysis of Extreme Climate Indices

**APPENDIX E:** Relationship of Indices with large scale circulation