Assessment of climate-change impacts on precipitation based on selected RCM projections

D.J. Peres*, M.F. Caruso and A. Cancelliere
University of Catania, Department of Civil Engineering and Architecture, Via S. Sofia, 64, 95123 Catania, Italy
*e-mail: djperes@dica.unict.it

Abstract: Regional climate models (RCMs) are essential to perform climate change impact studies. At the state of the art, many RCM products have limited accuracy, which reduces the reliability of climate change impact assessments. Bias correction techniques are commonly applied to obtain modified RCM data that are more consistent with observations. Nevertheless, these techniques have been criticized by some researchers, for their limited physical basis. In this study we propose a different approach, suitable when a relatively high number of different RCM simulations are available for the region of interest. The proposed approach consists in first evaluating the available RCM datasets by measures of agreement with observed data, and then to perform climate change impact assessment only with those RCM data complying with certain accuracy requirements. The approach is applied to assess potential future changes of precipitation in Sicily. To this aim, daily data sets of the Euro-CORDEX initiative are used for both intermediate and extreme greenhouse gas concentration emission scenarios (RCP 4.5 and RCP 8.5). Changes in future precipitation are computed in terms of widely used standard climate indices (ETCCDI), and statistical tests are applied to assess statistical significance of changes. Analysis of the accuracy of RCM data indicates that only 4 out of the 14 RCMs have limited biases. The ensemble of these four RCM models predicts an overall decrease of mean annual rainfall, as well as an increase of the maximum length of number of consecutive dry days, suggesting a potential future increase of water shortage problems and droughts in the studied region.

Key words: Climatic projections; EURO-CORDEX; Global warming; global circulation models; natural hazards

1. INTRODUCTION

Climate change due to uncontrolled greenhouse emissions is claimed to induce increases in water-related risks (IPCC, 2014). Future impacts of greenhouse emissions on climate can be assessed by perturbing global circulation models (GCM) with different emission scenarios defined at the international level (representative concentration pathways, RCPs). The 250-600 km spatial resolution of GCMs is increased by dynamical downscaling techniques, which yield regional climate model (RCM) products that can be used for an assessment at national or sub-national levels. Both GCM and RCM temperature and precipitation data are generally affected by significant biases, which can be spotted from comparisons with observations in the reference (past) period. When observations and climate model data are both available for the area of interest, it is very common practice to correct the climate model data, so they result more consistent with observations (Teutschbein and Seibert, 2012). This sort of calibration procedure has however some practical and theoretical downsides and it is not fully defendable from a physical standpoint since it can violate mass conservation principles (Ehret et al., 2012). In this paper we propose a different approach consisting in evaluating available RCMs on the basis of their ability to reproduce current climate, and then to perform the climate change impact assessment only by the set of more accurate models. This implies to implicitly assume that these models will be also the most accurate in predicting the future scenario. Here we apply this procedure with the aim of assessing future changes of precipitation in Sicily.
2. METHODOLOGY

The first phase of the methodology is aimed at deriving the set of most reliable RCM models. Hence the accuracy of each RCM in reproducing the observations in the baseline period (here assumed as 1971-2000) is assessed. Then, metrics of the goodness of reproduction are computed, and only the models with metrics above fixed thresholds are retained for further analyses. We consider performance metrics based on the relative errors (computed on a cell basis) of the mean annual precipitation:

\[ e_i[\%] = \frac{P_i^{(m)} - P_i^{(o)}}{P_i^{(o)}} \]  

where \( e_i \) is the relative error [%], \( i = 1, ..., N_c \) identifies the grid cell, \( P_i^{(m)} \) is the historical annual average precipitation estimated from the model in the \( i \)-th cell [mm]; \( P_i^{(o)} \) is the annual average precipitation observed in the \( i \)-th cell [mm].

Several indices can be computed based on these errors over a region of interest. Here we consider the mean error and the percentage of cells with relative error less than a certain amount. More specifically, only models with absolute mean error less than 15% and for which at least half of the cells have errors less than 25% are retained.

Once the reduced ensemble of models complying with the fixed accuracy requirements is defined, we assess climate change impacts on precipitation in terms of indicators suggested by the Expert Team on Climate Change Detection and Indices (ETCCDI) of the CCL/CLIVAR Working Group on Climate Change Detection, which can be classified based on the type of information they provide:

- Central tendency/cumulative amounts: the total annual precipitation and the mean daily intensity (SDII) belong to this category
- High-rainfall extremes: represent periods of intense rainfall, and thus are related to floods
  - Indices of this group include: Rx1day, Rx5day, R10mm, R20mm, R95p, R99p, CWD
- Low-rainfall extremes: indicate presence of prolonged periods of dryness or low rainfall, and are connected to droughts. In our analyses we consider the maximum number of consecutive days of dryness (CDD).

The reader is referred to the ETCCDI website (http://etccdi.pacificclimate.org/indices.shtml) for definitions of the indices mentioned above. To study the impact of climate change, for each RCM of the selected ensemble, the ETCCDI indices are computed for the historical and for three periods (2021-2050; 2041-2070; 2061-2090), in each emission scenario (RCP 4.5 and RCP 8.5). Then the variation of the index as the difference between its value in the future period and in the historical reference period is computed to quantify the changes for each RCM of the ensemble. Results given by the various models are then combined by testing the significance and the concordance of the projected changes. The Wilcoxon-Mann-Whitney test (see Helsel and Hirsch, 1992) has been applied to assess statistical significance of changes. This test has been applied in its one-sided version at a significance level of 10%, in testing for either positive or negative changes. Consequently, this means that the no-variation case corresponds to a two-sided test with 20% level of significance.

After the test has been applied, the concordance has been assessed. In particular, model can be concordant in predicting an increase, a decrease, or no-variation if a given percentage (>50%) of the models give significant changes in the same direction. Otherwise, models can be discordant, or the changes can be not significant. The results have been synthesized through the use of the so-called climate signal maps (Pfeifer et al., 2015), indicating the ensemble mean of variation by the color of the cell, and the direction of significant and concordant changes by an upward (positive) or downward (negative) arrow; whilst a dash indicates stable conditions and a question mark non-significant or discordant changes, respectively.
3. APPLICATION

The proposed procedure has been applied to assess potential future changes of precipitation in Sicily (Italy). For the validation of RCM climate models, daily rainfall grids have been derived from the observational dataset of the Sicilian regional water observatory, including a set of 508 rain gauges (which however worked in different and non-overlapping periods). This is the most accurate available rainfall dataset covering the historical reference period (1971-2000).

Table 1 lists the fourteen models from the EURO-CORDEX initiative (Jacob et al., 2014), providing climate products at the resolution of 0.11 degrees (approximately 12.5 km). As reported in the table, six different institutes produce the data, and the different datasets may be obtained by the same regional downscaling model (RCM) applied to a different global circulation model (GCM), and vice versa. For brevity, in this study the different models are identified with the institution’s acronym followed by the GCM.

Table 1. Ensemble of regional climate models from the EURO-CORDEX initiative considered in this study. Models selected based criterion A and B are reported in bold font (see text).

<table>
<thead>
<tr>
<th>ID</th>
<th>Acronym</th>
<th>Institute</th>
<th>GCM</th>
<th>RCM</th>
<th>Ensemble member</th>
<th>Ranking</th>
<th>Crit. A</th>
<th>Crit. B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EC-EARTH (DMI)</td>
<td>CLMcom</td>
<td>CNRM</td>
<td>CM5</td>
<td>CLMcom-CCLM4-8-17</td>
<td>r11i1p1</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>MPI-ESM-LR (CLMcom)</td>
<td></td>
<td>EC-EARTH</td>
<td>CLMcom-CCLM4-8-17</td>
<td>r12i1p1</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>CNRM-CM5 (CLMcom)</td>
<td></td>
<td>HadGEM2-ES</td>
<td>CLMcom-CCLM4-8-17</td>
<td>r11i1p1</td>
<td>14</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CNRM-CM5(SMHI)</td>
<td></td>
<td>MPI-ESM-LR</td>
<td>CLMcom-CCLM4-8-17</td>
<td>r11i1p1</td>
<td>12</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>EC-EARTH (SMHI)</td>
<td>CNRM</td>
<td>CNRM-CM5</td>
<td>CNRM-ALADIN53</td>
<td>r11i1p1</td>
<td>6</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>MPI-ESM-LR (SMHI)</td>
<td>DMI</td>
<td>EC-EARTH</td>
<td>DMI-HIRHAM5</td>
<td>r3i1p1</td>
<td>9</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>EC-EARTH (KNMI)</td>
<td>NorESM1-M</td>
<td>KNMI</td>
<td>CM5</td>
<td>KNMI-RACMO22E</td>
<td>r1i1p1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>EC-EARTH (CLMcom)</td>
<td>IPSL-INERIS</td>
<td>IPSL-CM5A-MR</td>
<td>IPSL-INERIS-WRF331F</td>
<td>r1i1p1</td>
<td>8</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>CNRM-CM5 (CNRM)</td>
<td>KNMI</td>
<td>EC-EARTH</td>
<td>KNMI-RACMO22E</td>
<td>r1i1p1</td>
<td>13</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>NorESM1-M (DMI)</td>
<td>CNRM-CM5</td>
<td>SMHI</td>
<td>RCA4</td>
<td>r1i1p1</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>IPSL-CM5A-MR (IPSL)</td>
<td></td>
<td>EC-EARTH</td>
<td>SMHI-RA4</td>
<td>r12i1p1</td>
<td>1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>IPSL-CM5A-MR (SMHI)</td>
<td>SMHI</td>
<td>HadGEM2-ES</td>
<td>SMHI-RA4</td>
<td>r1i1p1</td>
<td>10</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>HadGEM2-ES (CLMcom)</td>
<td></td>
<td>IPSL-CM5A-MR</td>
<td>SMHI-RA4</td>
<td>r1i1p1</td>
<td>11</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>HadGEM2-ES (SMHI)</td>
<td>MPI-ESM-LR</td>
<td>SMHI-RA4</td>
<td>r1i1p1</td>
<td>7</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. RESULTS

4.1 Evaluation and selection of the EURO-CORDEX models

Figure 1 shows box-plots of the relative errors in mean annual precipitation for each RCM. The box-plots depict the distribution of the relative error as computed by Eq. (1), so the outliers represent grid cells with extreme relative errors. For some models, huge relative errors can be present in certain cells; for one model (model 3), errors reach 100%, which means that the difference between RCM and observed mean annual precipitation is 10 times the observed precipitation itself (see model 3, CNRM-CM5 CLMcom); and though this may occur in some specific grid cells, still more than the 25% of the cells may exhibit errors above 200%. The mean and spreading of errors are large for a significant portion of the data also for other models (see models 9 and 13). Some models present a narrower spreading of the error, but still significant biases...
(such as models 12 and 14). Models 1, 2, 7, 10 and 11 have limited bias (absolute value less than 15%). Half of the models (1, 2, 5, 7, 8, 10 and 14) have narrow error spreading, that is the relative error of at least the 50% of cells is less than 25% in absolute value. Last two columns of Table 1 present the ranking of each model based on criterion A (absolute value of mean of the relative errors), and criterion B (proportion of cells having an absolute value of relative error less than 25%).

Only four out of 14 models fulfill the quality criteria (i.e. both A and B) model 1: CNRM-CM5 (SMHI); model 2: EC-EARTH (SMHI); model 7: CNRM-CM5 (CLMcom); and model 10: MPI-ESM-LR (CLMcom). This ensemble of models has been considered for assessing the changes in precipitation induced by the two scenarios RCP 4.5 (intermediate emissions) and RCP 8.5 (high emissions). In particular, signal climate maps have been derived from these selected RCMs, and are shown in the ensuing parts of this paper. This signal climate maps report concordance in either a positive (increase) or negative direction (decrease), or no-variation if at least 3 out of 4 models indicate the same direction of changes and these are significant according to the Wilcoxon-Mann-Whitney rank sum test. Variations are computed with respect to the rainfall data given by the corresponding RCM in the baseline period 1971-2000.

4.2 Changes in mean annual precipitation

Figure 2a shows for three future time periods (2021-2050, 2041-2070, 2061-2090), changes in total annual rainfall in Sicily related to RCP4.5 and 8.5 emission scenarios. For the first emission scenario, models agree in predicting a reduction of the total annual precipitation over Sicily, which however is significant and concordant only in some parts of mid-western and north-eastern areas of the region, where the decrease may reach 100 mm. Nevertheless, for a larger portion of the region significant changes are either discordant (periods 2021-2050 and 2061-2090) or not significant (period 2041-2070).

On the other hand, for RCP 8.5, climate models agree in predicting, for the period 2021-2050, a reduction of total annual precipitation almost over the entire region, with the exception of western Sicily and of some other sparse areas in the central-north part. In the period 2061-2090, reductions
of more than 100 mm are predicted for a large portion of the cells. It may be concluded that the high emission scenario may produce a reduction of yearly-accumulated precipitation with potential water scarcity problems and more severe droughts in the future.

Figure 2. Climate signal maps relatively to the two emission scenarios (RCP 4.5 and RCP 8.5) and three future temporal horizons. Variations are computed respect to reference period 1971-2000. Map for: a) total annual precipitation, b) R10mm, number of days with precipitation exceeding 10 mm, c) R95p, rainfall exceeding 95% percentile of reference-period daily precipitation, and d) CDD, maximum number of consecutive dry days.
4.3 Changes in high-rainfall extremes

Figure 2b shows the climate signal maps relative to the number of days with intense precipitation, (R10mm) defined as the number of days in a year with precipitation greater than 10 mm. As can be seen from the maps, the ensemble mean indicates a decrease of R10mm, with reductions that amount to a few (3-4) days in the whole future period, for both RCPs. However, for RCP4.5 the changes are seldom significant or concordant, with the exception of some sparse areas in the eastern or south-central parts of the island. For the RCP8.5 scenario, projections have a clearer trend, and indicate a reduction of R10mm in all central and almost all eastern parts of the region. Changes are clear for period 2061-2090, where R10mm variations can exceed 4 days.

Regarding the highly extreme precipitation amounts R95p (Figure 2c), no clear variations are indicated by the models. The ensemble mean shows that in the period 2021-2050 models tend to indicate mainly a decrease of R95p, but mostly the changes are not significant or concordant, unless for few cells. Indeed changes are significant in the case of the high emission scenario and periods 2021-2050 and 2061-2090, where significant decreases of R95p can be up to 40-60 mm in a relevant portion of Sicily.

4.4 Changes in low-rainfall extremes

Changes in the number of the maximum number of consecutive dry days (CDD) are shown in Fig. 2d. For both emission scenarios, models predict mostly an increase of CDD. The ensemble mean indicates, approximately 5-10 days of increase in many parts of Sicily. Again, only a limited portion of the island has significant changes for RCP4.5, being a non-variation the most frequent case in this scenario. Also, as for the other indices, in the RCP8.5 scenario, changes are high and significant for the last period, where the ensemble mean can indicate a variation up to 15-20 days.

5. CONCLUSIONS

Assessment of climate change is subject to a significant degree of uncertainty. Our application has shown that regional climate model products may be affected by significant errors (up to 1000% in some areas) in reproducing the precipitation regime in Sicily. Nevertheless, among the considered EURO-CORDEX ensemble, a limited, but still significant, number of the models (4 out of 14) have limited errors, and can thus be used to assess changes in rainfall induced by greenhouse emissions. The application has shown also that while the ensemble mean may indicate high variations of a given climatic feature (as represented by one or more ETCCDI standard indices), at the same time changes can be discordant or non-significant. Notwithstanding these uncertainties, there are some significant and concordant changes for the studied region. The analyses indicate more clear variations in the RCP8.5 scenario compared to the RCP4.5, even though qualitatively they are similar. Specifically, models indicate a reduction of annual rainfall even higher than 100 mm for the high-emission scenario in period 1961-2090. An increase in the number of dry days per year is also predicted quite clearly, which is again more significant for the RCP8.5 scenario than the RCP4.5, and can amount up to 20 days. Changes in heavy precipitation are less significant, and models are mostly concordant in predicting no variation respect the reference climate (1971-2000). Indeed, some significant decreases are predicted. Overall, analysis of the selected ensemble of EURO-CORDEX high-resolution RCMs suggests an increase of water shortage issues and droughts. On the other hand, results seem to do not support the hypothesis of an increase of heavy-rainfall triggered hazards induced by climate change, such as floods. This is somehow in agreement with trend analyses performed on observed time series in Sicily, that indicate no significant changes in extreme rainfall (Bonaccorso et al., 2005; Arnone et al., 2013), with the exception of short time scales (one hour or less). Thus, to assess variations at the sub-daily scale may be useful for a better understanding of potential impacts of climate change on floods, especially for small catchments
with concentration times less than few hours. This task may be accomplished by temporal downscaling of RCM daily products.

REFERENCES


