Climate change scenarios for precipitation extremes in Portugal

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This is a post-peer-review, pre-copyedit version of an article published in Theoretical and Applied Climatology. The final authenticated version is available online at: https://doi.org/10.1007/s00704-011-0528-3.

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ABSTRACT

Precipitation indices are commonly used as climate change indicators. Considering four CLIVAR-recommended indices, this study assesses possible changes in their spatial patterns over Portugal under future climatic conditions. Precipitation data from the regional climate model COSMO-CLM ensemble simulations with ECHAM5/MPI-OM1 boundary conditions are used for this purpose. For recent-past, medians and probability density functions of the CCLM-based indices are validated against station-based and EOBS-based (gridded daily precipitation data provided by the ECA&D project) indices. It is demonstrated that the model is able to realistically reproduce not only precipitation, but also the corresponding extreme indices. Climate change projections for 2071–2100 (A1B and B1 SRES scenarios) reveal significant decreases in total precipitation, particularly in autumn over northwestern and southern Portugal, though changes exhibit distinct local and seasonal patterns and are typically stronger for A1B than for B1. The increase in winter precipitation over northeastern Portugal in A1B is the most important exception to the overall drying trend. Contributions of extreme precipitation events to total precipitation are also expected to increase, mainly in winter and spring over northeastern Portugal. Strong projected increases in the dry spell lengths in autumn and spring are also noteworthy, giving evidence for an extension of the dry season from summer to spring and autumn. Although no coupling analysis is undertaken, these changes are qualitatively related to modifications in the large-scale circulation over the Euro-Atlantic area, more specifically to shifts in the position of the Azores High and associated changes in the large-scale pressure gradient over the area.

Keywords: extreme precipitation indices, future scenarios, Portugal, COSMO-CLM, ECHAM5/MPI-OM1, regional modelling

Abbreviations: CCLM, COSMO-CLM – Consortium for Small-Scale Modelling – Climate version of the Lokal-Model; GCM, Global Climate Model; GHG, greenhouse gas; IPCC, International Panel on Climate Change; MSLP, mean sea level pressure; NAO, North Atlantic Oscillation; RCM, regional climate model; SRES, Synthesis Report on Emission Scenarios; WMW, Wilcoxon-Mann-Whitney
1. Introduction

Precipitation is one of the most relevant climatic parameters, not only in describing the climatic conditions at a given location, but also in assessing the potential impacts of climate change on many environmental and socio-economic systems (e.g. Giorgi 2006). Precipitation is decisive for many systems that critically depend on its amounts and regularity, such as the design and management of irrigation systems, farm management systems, water supplies and hydropower generation. Precipitation extremes, including either meteorological droughts (dry spells with lengths above a pre-defined threshold; “dry extremes”) or episodes with extremely high precipitation amounts (e.g. above the 95th percentile; “wet extremes”), are also of major interest, mainly due to their potential damaging impacts (Trenberth et al. 2007). They often trigger severe hydrological droughts, devastating floods, and landslides, among other extreme events.

Taking into account the most recent climate change projections, this vulnerability might be further enhanced: the frequencies of occurrence and strength of precipitation extremes have not only sharply increased worldwide since the 1960s (Trenberth et al. 2007), but are also expected to grow until the end of this century (Meehl et al. 2007). Significant changes in the frequencies of occurrence of extreme precipitation events under human-driven climate change (due to anthropogenic radiative forcing) are projected throughout Europe (Beniston et al. 2007; Frei et al. 2006; Santos et al. 2007a). Most of these changes are related to a northward and/or eastward shift in the synoptic activity over the North Atlantic under future climate conditions (e.g. Bengtsson et al. 2006; Pinto et al. 2006; Ulbrich et al. 2009). In southern Europe, extensive irrigation might be required in response to higher temperatures, enhanced evapotranspiration, less precipitation and prolonged dry spells in future climate (Kjellström et al. 2011; Kostopoulou and Jones 2005; Sillmann and Roeckner 2008; Vicente-Serrano and Cuadrat-Prats 2007). However, the local climate change signal may be significantly different from the large-scale mean signal, highlighting the need of regional-scale assessment studies (Christensen et al. 2007).
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More specifically, Portugal is highly vulnerable to droughts, particularly taking into account the strong seasonality and irregularity of its precipitation regime (e.g. Santos et al. 2007b, 2009a). Further, precipitation in Portugal is strongly dependent on the large-scale atmospheric circulation within the Euro-Atlantic sector (e.g. Goodess and Jones 2002; Santos et al. 2005; Ulbrich et al. 1999). As an illustration, it has been shown that anomalously wet winters in Portugal, such as the 2009/2010 winter, are triggered by anomalies in the atmospheric flow over the North Atlantic (cf. Andrade et al. 2011; Vicente-Serrano et al. 2011).

Furthermore, future projections predict higher temperature extremes over mainland Portugal with increasing greenhouse gas (GHG) forcing (Carvalho et al. 2010; Ramos et al. 2011). On the other hand, the severest droughts in Portugal are often related to the development of strong and persistent anticyclonic ridges, associated with quasi-stationary and equivalent barotropic anomalies in the Eastern North Atlantic (Santos et al. 2009b). Droughts have also major impacts on Portugal, as 36% of the Portuguese continental territory is already susceptible to desertification under the mean climatic regime evaluated by the National Action Programme to Combat Desertification, (Rosário 2004). Higher temperatures and less precipitation will potentially amplify the vulnerability of some Portuguese regions to desertification, by increasing their economic and environmental problems, e.g. by increasing soil erosion and forest fires, and by decreasing agro-forestry-grazing productivity, aquifers recharge and biological diversity.

Therefore, precipitation change scenarios, not only focused on central tendency parameters (e.g. mean precipitation), but also on the projected changes in the occurrence of extremes, are of high relevance in developing suitable mitigation/adaptation measures at local and regional scales, which might effectively prevent the negative impacts of climate change on the environment and on a large number of human activities. Future scenarios, specifically developed for Portugal using global-regional numerical model chains, are thereby expected to provide useful information for stakeholders, decision-makers and policy-makers.

Several extreme precipitation indices are commonly used as indicators for the detection and quantification of possible climate change signals (e.g. Peterson et al.
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2001; Sillmann and Roeckner 2008; Tebaldi et al. 2006). In general, these
indicators represent events that occur several times per season, having then more
robust statistical properties than other measures of extremes located in the very far
tails of the distributions (e.g. Alexander et al. 2006; Frich et al. 2002). Aiming at
isolating the likely temporal changes in the spatial patterns of precipitation
extremes over the Portuguese mainland, four widely known indices are selected in
this study: three of them are specifically devoted to the analysis of “wet extremes”
and one to the analysis of “dry extremes”. As such, the selected indices jointly
provide information from both tails of the distributions. Although these four
indices represent different perspectives of the extreme events, they are
undoubtedly interrelated, as will be apparent in the discussion of the results
below.

The first goal of the present study is to assess whether the selected global-regional
numerical model chain is able to replicate not only precipitation totals, but also its
extreme precipitation indices in Portugal. Secondly, the potential changes in these
extreme indices under future climate projections are analysed. Section 2 briefly
describes the regional model, the precipitation indices and the methodology. In
Section 3.1, the model-based indices are validated by observation-based indices,
computed using both weather station data and gridded daily precipitation. Future
climate projections for the indices are presented in Section 3.2. Lastly, a
discussion of the main results is presented in Section 4.

2. Data and Methods

2.1 Regional model

Climate modelling using Earth system numerical models is the most valuable tool
for assessing climate change at global, regional and local scales (Randall et al.
2007). Climate change projections are commonly generated by varying the GHG
concentrations in the Earth system models (boundary conditions), according to
pre-specified emission pathways based on likely storylines of the human
development and population growth. The International Panel on Climate Change
(IPCC) produced a number of family scenarios until the end of the 21st century,
described in its Synthesis Report on Emission Scenarios (SRES), which cover a
feasible level of uncertainty and have been widely applied in climate research and
in modelling the impacts of climate change on a vast number of systems
(Nakićenović and Swart 2000).

However, the output fields from global climate models are commonly defined
over relatively coarse spatial grids, not allowing assessments at local/regional
scales. Therefore, regional climate models nested in global models have been used
as a dynamically-coherent downscaling strategy, generating higher resolution
datasets. In the present study, climate change assessments for Portugal are based
on simulations produced by the state-of-the-art regional climate model COSMO-
CLM (Consortium for Small-Scale Modelling – Climate version of the Lokal-
Model; Böhm et al. 2006, Rockel et al. 2008; hereafter CCLM). Model output is
available over a regular grid of 0.165° latitude x longitude (grid size of about 18
km). This grid resolution is higher than the 25 km grid size in the ENSEMBLES
project models (van der Linden and Mitchell, 2009), which is an important
advantage, particularly when carrying out regional climate change assessments
such as in the present study.

The CCLM is nested in the ECHAM5/MPI-OM1 global circulation model for
both past and future climate conditions (Roeckner et al 2006; hereafter
ECHAM5). The ECHAM5 simulations have been extensively used in many
previous studies. (e.g. Bengtsson et al. 2006; Pinto et al. 2007; Demuzere et al.,
2009). As an illustration, Pinto et al. (2007) analyzed the impact of the enhanced
GHG forcing on the synoptic activity using ECHAM5 simulations. For the CCLM
simulations, a two-member ensemble is used in the present study for both a
recent-past period (C20, 1961–2000, cf. Lautenschlager et al. 2009a, b) and two
future scenarios (IPCC SRES A1B and B1 scenarios, 2071–2100; cf.
Lautenschlager et al. 2009c-f). The SRES A2 scenario runs are currently not
available. The A1B scenario corresponds to a balance across all energy sources
(fossil and non-fossil energies), while the B1 scenario features a more
environmentally sustainable world (Nakićenović and Swart 2000); during the 21st
century, the carbon dioxide concentrations raises from 367 ppm (year 2000) to
540 ppm (B1) and 703 ppm (A1B, both year 2100). Data from these CCLM runs,
extracted only for a sector covering the Portuguese mainland (Portuguese sector
hereafter: 36.8°–42.2°N; 9.6°–5.8°W; 560 grid-boxes), are used here. The two
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ensemble members have very similar signals, as it is exemplified for the A1B scenario (Figs. A1-A8). Therefore, in all upcoming analysis, they are merged and jointly analysed for the same period and scenario, doubling the respective sample sizes.

The skilfulness of the CCLM in reproducing different atmospheric fields (e.g. Hollweg et al. 2008) and precipitation characteristics (e.g. Bachner et al. 2008; Roesch et al. 2008) has already been documented. The CCLM data used here has already been considered in a large number of climate impact studies (e.g. Früh et al. 2011; Malheiro et al. 2010; Panferov et al. 2009). Nevertheless, a complementary model validation is undertaken herein, now giving more emphasis to the CCLM skill in simulating the extreme precipitation indices in Portugal.

Despite the model validation for the present-day conditions, it must be stressed that this is only a 'necessary but not sufficient' condition for assessing the reliability of future projections.

2.2 Precipitation indices

Four extreme precipitation indices recommended by the joint project CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (http://cccma.seos.uvic.ca/ETCCDI/indices.shtml) are selected: Rx5day, R95T, R95pTOT and CDD (Frich et al. 2002; Karl et al. 1999; Peterson 2005). The Rx5day index is defined as the highest consecutive 5-day precipitation total (in mm), providing then a measure of the medium-term precipitation totals. The R95T index is computed as the ratio between R95pTOT and PRCPTOT, where R95pTOT (in mm) is the total precipitation falling in days with amounts greater than the corresponding long-term 95th percentile (calculated only for wet days and for the baseline period 1961–1990) and PRCPTOT is the total precipitation falling in wet days (in mm). A wet day is defined as a day with an accumulated precipitation of at least 1.0 mm (otherwise it is a dry day). Hence, the R95T represents the dimensionless fraction of total precipitation falling during extreme rainfall events or, in other words, the contribution of extreme events to total precipitation (in %). Finally, CDD is defined as the maximum length of a dry spell (in days per season). The extreme indices are computed at all CCLM grid-boxes within the Portuguese sector for each meteorological season separately (winter:
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This seasonal analysis is plainly justified when considering the aforementioned strong seasonality of the Portuguese precipitation regime (Gallo et al. 2011; Trigo and DaCamara 2000). For the CCLM validation, the indices are also calculated for a network of 13 weather stations in Portugal (Fig. 1). Daily precipitation recorded at seven meteorological stations (Barcelos, Porto, Vila Real, Bragança, Coimbra, Lisboa and Beja) was provided by the European Climate Assessment & Dataset (ECA&D; http://eca.knmi.nl/), while data from the six remaining stations was supplied by the Instituto Nacional da Água (INAG). Only daily precipitation time series without data gaps within a minimum length of 30 years were retained. Some stations were also rejected because of their close proximity to other stations. Data quality checking of the seven ECA&D stations was already undertaken within this project (e.g., Klein Tank et al. 2002; Wijngaard et al. 2003). The INAG stations were quality-controlled and comprehensively studied for homogeneity by Costa and Soares (2009a, 2009b).

2.3 Methodological framework

2.3.1 CCLM validation

The CCLM-based indices computed for the recent-past period (1961–2000) are compared to those based on observational data, recorded at the network of 13 Portuguese weather stations (Fig. 1); the relatively low density of available weather stations in central Portugal is noteworthy. The station-based indices are compared to the corresponding CCLM-based indices at the grid-boxes that enclose each station (grey grid boxes in Fig. 1). This comparison is carried out by applying both the nonparametric Wilcoxon-Mann-Whitney test (WMW; Mann and Whitney 1947; Wilcoxon 1945) for equal medians and the two-sample Kolmogorov-Smirnov test for equal probability density functions. As previously explained, the two-member ensemble medians and probability density functions are used for validation, though the validation outcomes are very similar to those obtained using single member statistics (not shown). The WMW test can be summarised as follows. Simple linear rank statistics have the form:
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\[ S = \sum_{j=1}^{n} c_j a(R_j) \]  

(1)

where \( R_j \) is the rank of observation \( j \); \( a(R_j) \) is the score based on \( R_j \); \( c_j \) is an indicator variable denoting the group (i.e., period) to which the \( j \)-th observation belongs; and \( n \) is the sample size. Wilcoxon scores are simply the ranks:

\[ a(R_j) = R_j \]  

(2)

Using Wilcoxon scores in the linear rank statistic for two-sample data (Eq. 1) produces the rank sum statistic of the WMW. Standard asymptotic methods to compute the \( p \)-values of the test imply the assumption that the test statistic follows a particular distribution when the sample size is large enough. Asymptotic results might be unreliable, not only when the sample size is not large, but also when the distribution of data is sparse, skewed or heavily tied. If the asymptotic assumptions are not met, the asymptotic \( p \)-values are not reliable approximations to the true \( p \)-values. In such situations, exact \( p \)-values can be estimated by a Monte Carlo simulation.

The \( p \)-values of the test are estimated using Monte Carlo simulations with 10 000 samples. The random sample of 10 000 tables is generated through the algorithm proposed by Agresti et al. (1979), which generates tables in proportion to their hypergeometric probabilities conditional on the marginal frequencies. Each sample table has the same total sample size, row totals and column totals as the observed table. For each sample table, the value of the test statistic is computed and compared to the value obtained for the observed table. When estimating a right-sided \( p \)-value, for example, the \( p \)-value estimate equals to the relative frequency of sample tables for which the test statistic is greater than or equal to the observed test statistic.

In order to improve the CCLM validation, the observational gridded daily precipitation obtained from the EOBS dataset and provided by the ECA&D project (Haylock et al. 2008) is also used. Being a gridded dataset, with a spatial aggregation of observations, it enables a more direct validation of the CCLM output. However, it does not substitute station data, which does not suffer from gridding biases that may be particularly significant when considering daily precipitation. It should also be noted that the EOBS grid has a spatial resolution of
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25 km (as in the ENSEMBLES-project models) that does not directly correspond to the CCLM grid. Hence, the nearest EOBS grid cell from each CCLM grey cell in Fig. 1 (with the closest central points) is extracted for the CCLM validation. The smoothed topography in the EOBS grid may also explain important discrepancies between EOBS-estimated medians and those obtained from station data, despite being both observational datasets; this is particularly pertinent over the northern half of Portugal, where orography is generally quite complex. It is still worth noting that the validation of regional climate model (RCM) data against observations is not trivial. Model variables are averages over a grid-box area, while station observations are point values that may be more or less representative of a certain area. To assess this problem, a number of model output statistic techniques have been developed (cf. Maraun et al. 2010 for a review). However, this problem is considered to be less important when considering aggregated variables (over time), as the aggregation makes the RCM output and observations more comparable. Therefore, no model output statistics is performed in this study.

2.3.2 Climate change assessment

The seasonal distributions of the four CCLM-based indices are tested for their normality, both in the recent-past period (1961–2000) and in the future period (2071–2100), through the application of the Shapiro-Wilk test (Shapiro and Wilk 1965) to all 560 grid-boxes (Portuguese sector). The normality hypothesis is rejected at the 95% confidence level in most of the seasonal indices and for most grid-boxes, particularly in the recent-past period (1961–2000). Taking for example the winter two-member ensemble CDD index, the normality hypothesis is rejected at 93% of the grid-boxes in 1961–2000, while it is rejected at only 23% in 2071–2100. As a result, nonparametric approaches are more appropriate for the current statistical analysis and are used here. As previously stated, climate change projections for the two-member ensemble indices are calculated and their statistical significance is assessed through the application of the one-sided WMW test to all 560 grid-boxes. Hence, the WMW one-sided tests are used both to validate the model outputs using observational
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datasets and to compare the two-member ensemble medians of the indices in 2071–2100 with their values in 1961–2000 (recent-past period).

3. Results

3.1 CCLM validation for recent climate conditions

The model validation is carried out for the recent-past period (C20; 1961–2000), when the CCLM is forced by historical records of GHG emissions, providing thus possible representations of recent climatic conditions that can be compared to historical data. In order to compare the two-member ensemble medians (M) and probability density functions (PDF) of the CCLM-based indices with the corresponding station-based and EOBS-based indices (PRCPTOT, Rx5day, R95T, R95pTOT and CDD), the hypothesis testing results for equal M (WMW test) and for equal PDF (two-sample Kolmogorov-Smirnov test applied to the centred indices) are summarized in Tables 1–3 for each season in 1961–2000. In these tables, grey cells indicate a rejection of the null hypothesis at a 1% significance level. S or E characters specify whether the null hypothesis is rejected based on station or EOBS data, respectively. Overestimation (underestimation) of the medians by CCLM are also indicated by ‘+’ (‘-’). As summer precipitation is generally very scarce and highly irregular in continental Portugal (e.g. Trigo and DaCamara 2000), it does not fulfil the basic assumptions for a proper application of the hypothesis tests and will then not be considered in this testing.

A close inspection of the hypothesis testing outcomes reveals that the CCLM clearly tends to overestimate precipitation (PRCPTOT) over northern and central-western Portugal (Barcelos, Bragança, Vila Real, Porto, Coimbra and Lisboa), while it tends to underestimate precipitation in central-eastern Portugal (Aguiar da Beira and Almeidinha). Although the topographic barrier effect in central and northern Portugal, imposed by mountain ranges that are predominantly north-south-oriented, contributes to an actual strong contrast between west-side (windward) and east-side precipitation (leeward), the validation results show that the CCLM tends to overestimate this barrier effect by overestimating (underestimating) PRCPTOT in the west (east) side. Similar considerations can be made for the most southwestern part of the country, where the effect of the
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smaller-scale orographic barrier is also exacerbated by the CCLM, explaining the
overestimations (underestimations) of PRCPTOT in Bravura (Palheiros). These
model biases in PRCPTOT are particularly pronounced in winter, when frontal
and orographic precipitations prevail, enhancing the topographic barrier effect.
The previous shortcomings from the CCLM simulation are also mostly reflected
in Rx5day (cf. Tables 1–3), where analogous biases are apparent. This can be
easily understood, since this index represents precipitation amounts accumulated
in a consecutive 5-day period. Some repercussions of the PRCPTOT biases in
R95pTOT are also identified, though to a much lesser extent than in Rx5day and
without significant impact on the R95T derived-index. Lastly, no significant
deviations in the CDD index are detected, which means that the PRCPTOT biases
tend to produce biases in the daily precipitation totals, rather than in the frequency
of occurrence of rainy days. In fact, for all selected weather stations, the simulated
numbers of rainy days per season do not show significant biases (not shown).
All these biases in the indices’ medians are offset when taking differences
between two periods (climate change signal). Although bias in medians can be
easily calibrated in most of the applications, they also suggest some limitations in
modelling the physical processes underlying precipitation. Conversely, biases in
the shape of the simulated distributions are generally more difficult to correct,
being important limitations of model simulation. No important biases in the
shapes of PRCPTOT (apart from the winter in Aguiar da Beira), Rx5day and
CDD are found, which highlights the CCLM skilfulness in reproducing the
distributions of daily precipitation in Portugal.
Nevertheless, significant biases can be found in the distributions of R95pTOT,
mainly in autumn and spring, with direct implications also in the distributions of
R95T. This constraint only applies to southern Portugal (Azinheira, Beja,
Palheiros, Bravura and Castro Marim) and this spatial coherency suggests some
inability of the CCLM in simulating extreme precipitation in this region. A more
detailed analysis showed that the CCLM tends to overestimate the precipitation
amounts occurring in some extreme events (not shown). Consequently, the
contribution of extreme precipitation events to total precipitation tends to be
overestimated by the RCM, yielding a deviation in the shape of the R95pTOT and
R95T distributions and ultimately contributing to the rejection of the null-
3.2 Climate change projections

After the validation of the CCLM-based indices for recent climate conditions, we now evaluate the same two-member ensemble indices and precipitation totals for a period at the end of the current century (2071–2100; 30 years), following the A1B and B1 SRES scenarios, and compare them to recent climate conditions (1961–2000; 40 years). A sensitivity study using a 30-year period for quantifying the recent-past conditions (either 1961-1990 or 1971-2000) revealed no significant changes in the results (not shown).

Although changes in the accumulated precipitation values are of utmost relevance in regional climate change assessments, the projected changes in extremes might also play a key role in the decision-making processes. In this way, the statistical significance of the changes in the selected four extreme indices (Rx5day, R95T, R95pTOT and CDD) is assessed here for each season separately. Since the projected changes in the extreme precipitation indices exhibit distinct local and seasonal patterns, Portugal can be divided into three regions. These regions roughly correspond to the northwestern, northeastern and southern Portugal, where the Tejo River delineates the boundary between northern and southern Portugal. Administrative divisions represent the boundaries between northwestern and northeastern Portugal (cf. limits outlined in Figs. 3-5). Table 4 discriminates the most significant changes within each region and provides a summary of the results described below. Although the A1B scenario implies more significant changes than B1 (lower GHG forcing), these changes are of the same signal.

3.2.1 Precipitation (PRCPTOT)

The projected changes in the annual precipitation under the A1B scenario reveal an overall decrease throughout Portugal, apart from some few exceptions in the interior north (Fig. 2); north-western Portugal is projected to experience the most remarkable decrease (less 200–400 mm per year). For the seasonal totals, the projected changes are largely coherent with those found for the annual totals, with the exception of winter, when precipitation increases are projected over northern
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Portugal. Statistical significances are not assessed in these patterns because, as shown before, daily precipitation is far from being normally distributed and the WMW tests are applied below to the differences in the PRCPTOT medians. Hence, the climate change signal for the annual precipitation in Portugal mainly reflects a widening of the dry season from summer to autumn and spring. The increases in wintertime precipitation are not generally large enough to offset the drying trend in northwestern Portugal, but can explain the absence of a clear trend in the annual totals over northeastern Portugal.

Results of the non-parametric WMW tests for the annual precipitation totals (PRCPTOT) under A1B (Fig. 3) are in clear agreement with the projected changes in the precipitation amounts (Fig. 2), though the most significant decreases are now verified over southern Portugal. Precipitation in this region is already at very low levels, making decreases of 200 mm very substantial. The statistically significant increases in wintertime precipitation over northeastern Portugal are still noteworthy (Fig. 3). In fact, they tend to compensate the downward precipitation trends in the other seasons, leading to non-significant changes in the annual amounts over this region. The strong decreases (at a 99% confidence level) in autumn precipitation over northwestern and southern Portugal are also worth mentioning. Similar results are obtained for the B1 scenario in autumn and annual values (Fig. A9), but with less significant decreases in precipitation (lower forcing scenario). Winter precipitation is also expected to decrease over the south. In spring, B1 is in clear contrast with A1B (Figs. A9 and 3, respectively), showing no significant changes throughout Portugal.

3.2.2 Autumn indices

For autumn, the significant increase (at a 99% confidence level) in the CDD index is the most remarkable change in the precipitation regime in Portugal (Fig. 4). The length of the dry spells is predicted to increase, on average, 9 days in the south and 6 days in the northern part of the country (Table 4). The other indices do not depict clear and spatially consistent signals, except the Rx5day index which is predicted to decrease in a large area of the south. In the B1 scenario, the significant increase in the CDD index over the country is still remarkable (Fig. A10), whereas the significant decreasing patterns of the
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Rx5day index are only located around the southern coastline. The R95T index presents a highly significant increase in the Atlantic Ocean along the northwestern coast in the A1B scenario (Fig. 4), whereas significant increases also appear inland in the B1 scenario (Fig. A10).

3.2.3 Winter indices

For winter, however, there is a significant increase in the contribution of extreme precipitation to the total amounts (R95T) over Portugal (at least 6% on average; cf. Table 4), while no strong signal exists for the CDD index, except in the southernmost part of the country (Fig. 5). The Rx5day and R95pTOT indices tend to be a direct manifestation of the changes in the precipitation amounts (Fig. 2), with most of the significant increases occurring over northern Portugal. In fact, according to Table 4, the highest consecutive 5-day precipitation total (Rx5day) is expected to increase, on average, at least 18 mm in the north, which is consistent with the expected increase of at least 49 mm in the total amount of precipitation associated with extreme events (R95pTOT). The B1 scenario results (Fig. A11) imply less significant changes than A1B for the “wet extremes”.

These outcomes show that the CCLM climate change projections (under the A1B and B1 SRES scenarios) for precipitation in Portugal suggest an overall increase in the contribution of extreme precipitation events to total precipitation in winter. It is also worth mentioning that, under the B1 scenario, the Rx5day index is predicted to significantly decrease in the south, while the pattern of increase in the length of the dry spells (CDD) extends over a larger area from the south to the northeast.

3.2.4 Spring indices

Finally, in spring similar results to autumn are obtained (Figs. 6 and A12). There is a pronounced increase in the length of the dry spells (CDD) over the whole country: the CDD is predicted to increase, on average, 11 days in southern Portugal and at least 8 days in the north (Table 4). Such increase might yield more frequent and severe meteorological droughts that commonly play a key role in triggering hydrological droughts.
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Spring precipitation is projected to undergo a significant decrease, which is accompanied by a clear extension of the “dry spells”, but without clear changes in the occurrence of “wet extremes”.

3.3.5 Dynamical features

Both sides of the precipitation extremes (extremely high precipitation events and meteorological droughts) are projected to become more frequent under human-driven climate change. Apart from some differences in detail, the main results for both scenarios are quite similar (Figs. 4–6 and A10–A12). However, more “dry extremes” (CDD) and less “wet extremes” can be clearly identified in B1 than in A1B in winter. A decrease in PRCPTOT is apparent, particularly in autumn, and over northwestern and southern Portugal. The contribution of extreme precipitation to total precipitation (R95T) is also expected to increase, mainly in winter and spring over northeastern Portugal. The length of dry spells (CDD) is also projected to increase throughout Portugal, primarily in autumn and spring.

In order to understand the dynamical features underlying the previous changes in the precipitation extreme indices, the mean sea level pressure (MSLP) fields for the recent-past period (1961–2000) and for the future period (2071–2100) under A1B and B1 are now analysed using the ECHAM5 data for the whole North Atlantic / European Region (Fig. 7 and A13). For the recent-past period, ECHAM5 underestimates MSLP north of the British Isles, and slightly overestimates MSLP over the Mediterranean, leading to a stronger latitudinal pressure gradient than in reality (e.g., Demuzere et al., 2009). However, ECHAM5 reproduces the mean MSLP pattern over the North Atlantic / European area better than most GCMs (Donat et al., 2010). For future climate conditions, a slight northward extension in the climate-mean Azores high pressure system is depicted in these patterns in both spring and autumn (Fig. 7), explaining the projected precipitation decreases in these two seasons (Fig. 2). In winter, however, there are a clear strengthening and significant shifts in its location, but with significant differences between both scenarios: the maximum positive anomaly in the MSLP is found northward of Iberia in B1 (Fig. A13), whilst it is found over the Mediterranean Basin in A1B (Fig. 7). These differences justify the contrasting projections for winter precipitation, since the northern half of Portugal
Climate change and precipitation extremes in Portugal

is much more exposed to the westerly winds and to the associated cyclonic (rain-generating) systems in A1B than in B1. Consequently, we can state that part of the projected changes in precipitation and in its extreme indices, obtained with the ECHAM5/CCLM model chain, reflect the shifts in the large-scale circulation over the Euro-Atlantic region, as observed in ECHAM5 under future climate conditions. However, these large-scale changes cannot explain all the changes in precipitation, particularly in its extremes. In fact, the atmospheric dynamics leading to precipitation extremes is complex and cannot be exclusively related to large-scale changes.

4. Summary and discussion

The present study investigated possible temporal changes in the spatial patterns of precipitation in Portugal, based on simulations with the regional climate model CCLM for current (1961-2000) and future (2071-2100) climate conditions under the A1B and B1 SRES scenarios. With this aim, total precipitation and four CLIVAR-recommended indices (Rx5day, R95T, R95pTOT and CDD) were analysed. The validation against station data shows that CCLM is able to reliably reproduce the main statistical characteristics of precipitation in Portugal, better for the northern than for the southern half. Similar results were obtained with the EOBS-derived indices. Regarding a possible climate change signal, results give clear evidence for a future increase in both the occurrence and strength of the precipitation extremes over Portugal (following both scenarios). Typically, the results for the B1 scenario (more environmentally sustainable than the A1B) revealed, as expected, less significant changes in the precipitation totals and respective indices than for the A1B, but their spatial patterns tend to be very similar; A1B might be considered an intermediate emission scenario. Globally, the western half of the country (windward side) tends to be subject to more significant decreases in precipitation amounts than its eastern half (leeward side). There is a projected decrease in the precipitation totals over most of the country, particularly in autumn over northwestern and southern Portugal. Extreme precipitation is also more likely in the future, mainly in winter and spring over northeastern Portugal (R95pTOT and
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R95T). The length of dry spells (CDD) is also expected to increase over most of the country, particularly in spring and autumn. These results are in line with the recorded trends in extreme precipitation during the last century. In the context of the Iberian Peninsula, Gallego et al. (2011) found a significant decrease in light rainfall days for 1903–2003 over southern Portugal. In addition, Costa and Soares (2009a) found an increase in the length of dry spells and a tendency towards drier climatic conditions for 1955–1999 in that same region. A decreasing trend in March precipitation over the twentieth century for mainland Portugal was also reported in other studies (e.g. de Lima et al. 2010; Trigo and DaCamara, 2000).

Our results are also consistent with those obtained by Sillmann and Roeckner (2008), which have also used the ECHAM5 simulations with the A1B and B1 scenarios. They concluded that the CDD index is projected to substantially increase over southern Europe; the longest dry period within a year is projected to be prolonged by 1 (1.5) months at the end of this century under the B1 scenario (A1B scenario). However, the projected changes in the “wet extremes” over the Mediterranean are less apparent in the aforementioned study than in our study, which might be due to the relatively coarse grid (low spatial resolution) of the global model compared to the CCLM output considered here.

The large-scale circulation over the mid-latitude North Atlantic is strongly connected to the position and intensity of the Icelandic low and of the Azores high, with Portugal being more or less affected by westerly winds that carry moist air originated in the North Atlantic (e.g. Santos et al. 2005; Trigo et al. 2002). Precipitation in Portugal is indeed largely favoured by the negative phase of the North Atlantic Oscillation (NAO), particularly during winter (e.g. Andrade et al. 2011; Trigo and DaCamara 2000; Ulbrich et al. 1999).

Based on the spatial patterns of the changes in the indices, Portugal was divided into three regions (northwest, northeast and south) that are also characterized by distinct precipitation regimes. In fact, precipitation in the north is predominantly frontal and orographic, whereas it tends to be more associated with cyclogenetic activity in the south (Trigo and DaCamara 2000). Additionally, as the mountain ranges located north of the Tejo River have a significant north-south orientation, on their windward side, forced lifting of approaching air masses causes orographic
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precipitation. As a result, precipitation will decrease on the leeward side, being
the leeward slopes drier and warmer than the windward slopes (Föhn effect).
Therefore, there is a distinct precipitation pattern in the western (windward-side)
and eastern (leeward-side) regions northwards of the Tejo River, justifying the
separation between northwestern and northeastern Portugal. Orographic effects
are much weaker in southern Portugal. All these spatial features are well captured
by the CCLM, despite some overestimation of the orographic effects, and clearly
support the decision to depict the three regions considered in the present study.
Future scenarios for precipitation and its extremes mostly reflect the projected
strengthening and displacement of the Azores high pressure system, particularly
for winter, which are also manifested as an upward trend in the NAO index
(stronger and more frequent positive phase; cf. Pinto et al. 2007; Stephenson et al.
2006), leading to more stable and drier atmospheric conditions in the future (Trigo
et al. 2002). These findings are also widely supported by many previous studies
(Haylock and Goodess 2004; Kyselý and Domonkos 2006; Pauling et al. 2006;
Scaife et al. 2008) and are related with a northward and/or eastward shift of the
North Atlantic storm tracks under future climate conditions (e.g. Bengtsson et al.
2006; Pinto et al. 2006; Ulbrich et al. 2009). These dynamical changes also
explain the widening of the summertime dry season. These changed dynamical
features are also largely unfavourable to the establishment of the moist westerly
winds over Portugal, coming from the North Atlantic, and to orographic
precipitation (mountain barrier effects), which is currently an important
precipitation mechanism over the western half (windward side) of the country.
The precipitation scenarios here presented are likely to have strong impacts on the
water cycle in Portugal, by contributing to a decrease in the water fluxes and
eventually to a weakening of the entire cycle. Similar results have also been
reported when investigating the impacts of climate change on the water resources
of the Tejo and Guadiana Rivers using future scenarios derived from the regional
climate model HadRM3H (Kilsby et al. 2007). Water supply and quality may then
be strongly affected. In fact, recent studies have documented the relevance of the
regular occurrence of rainy winters to refill the water dams in Portugal (Andrade
et al. 2011). This finding is also very relevant when planning the Portuguese
electricity production (as well as its distribution and consumption), since
Climate change and precipitation extremes in Portugal

Hydropower generation represents an important fraction of the national electrical production. In fact, considering the climate projections derived from the HadCM3 global climate model, the developed hydropower potential in Portugal is expected to decrease 22.1% by the 2070s (and 44.4% using the ECHAM4/OPYC3 model) (Lehner et al. 2005). The ratio of renewable energy production might then be negatively affected, which implies a growth in the fossil fuel consumption (and imports), as well as in the national GHG emissions.

Furthermore, the Portuguese agro-forestry sector tends to be highly water-demanding, being many of these activities based on irrigation systems that rely on artificial water reservoirs and dams, which are in turn critically dependent on precipitation. The greater vulnerability of many economically important cultivars (e.g. grapevines, olive trees, pine trees, among many others) to excessive water stress will also be a major challenge.

The identified increase in the dry spell length in spring and autumn, and the associated extension of the dry season from spring and autumn, will also have consequences in terms of forest wildfires, which have affected over 3 million ha in Portugal between 1980 and 2007 (Moriondo et al. 2006). The extent of burnt area in Portugal is controlled by two main factors (Pereira et al 2005; Verde and Zêzere 2010): (i) a relatively long dry period with absence of precipitation in late spring and early summer; and (ii) the occurrence of very intense dry spells during days of extreme synoptic situations. Thus, future climate conditions should favour wildfire activity. This consideration in line with other studies (e.g., Carvalho et al. 2010; Moriondo et al. 2006), which estimated an increase in the severity and length of the fire season with increasing GHG forcing.

Furthermore, increased drought periods, forest fires and irregular precipitation regimes tend to decrease vegetation cover and ecological resistance, thereby increasing erosion prone areas. All these impacts of climate change in soil and water may intensify the desertification susceptibility of large areas, particularly in southern and northeastern Portugal.

Finally, it should be emphasized that the results presented here are based on a single global-regional model chain (ECHAM5-CCLM). Despite the existence of some level of uncertainty in our results, they are largely supported by many previous studies that give clear evidence for a drying of southern Europe in...
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response to changes in the large-scale atmospheric flow (e.g. Beniston et al. 2007; Haugen and Iversen 2008; Kilsby et al. 2007; Kjellström et al. 2011; Sillmann and Roekner 2008; Trenberth et al. 2007). In future work we aim at extending this analysis to outputs from other regional model runs with multiple GCM forcing, including those from the ENSEMBLES project dataset (Hewitt and Griggs, 2004; van der Linden and Mitchell, 2009).

Acknowledgments

We thank the MPI for Meteorology (Hamburg, Germany), the WDCC/CERA database and the COSMO-CLM community for providing the COSMO-CLM data. We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://eca.knmi.nl).

Appendix: Supplementary material

This Appendix presents a set of additional figures addressing the results obtained for the B1 SRES scenario and for the two ensemble members of the A1B SRES scenario.

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Figure legends

Fig. 1 Map of Portuguese mainland showing the CCLM grid (~18 km) within the selected geographical sector, the locations of the 13 meteorological stations in Portugal (black circles) and the corresponding grid-boxes used for model validation (in grey)

Fig. 2 Mean precipitation totals (two-member ensemble means) over continental Portugal (in mm) as simulated for recent-past climate conditions: (a) annual; (b) autumn; (c) winter; (d) spring and (e) summer amounts. The (f–j) maps show the respective differences between future climate conditions under the B1 SRES scenario (2071–2100) relative to recent-past climate conditions (1961–2000). The (k–o) maps are as (f–j) but under the A1B scenario

Fig. 3 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the two-member ensemble medians of PRCPTOT between future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000) in: (a) autumn; (b) winter; (c) spring and (d) annual values

Fig. 4 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the autumn two-member ensemble medians of each index for future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD

Fig. 5 As in Fig. 4, but for winter

Fig. 6 As in Fig. 4, but for spring

Fig. 7 Composites of the mean sea level pressure (in hPa) within the Euro-Atlantic sector simulated by the ECHAM5 for the recent-past period (1961–2000; left panels) and for the future period (2071–2100; right panels) under the A1B SRES scenario in: (a) autumn; (b) winter; (c) spring. The anomalies between future and recent-past fields are also shown on the right panels (shading). Only differences with a statistical significance level of 5% are depicted

Fig. A1 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the ensemble member 1 medians of PRCPTOT between future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000) in: (a) autumn; (b) winter; (c) spring and (d) annual values

Fig. A2 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the autumn ensemble member 1 medians of each index for future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD

Fig. A3 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the winter ensemble member 1 medians of each index for future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD
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Fig. A4 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the spring ensemble member 1 medians of each index for future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD

Fig. A5 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the ensemble member 2 medians of each index for future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000) in: (a) autumn; (b) winter; (c) spring and (d) annual values

Fig. A6 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the autumn ensemble member 2 medians of each index for future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD

Fig. A7 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the winter ensemble member 2 medians of each index for future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD

Fig. A8 Results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the spring ensemble member 2 medians of each index for future climate conditions under the A1B SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD

Fig. A9 As Fig. 3 but for the B1 SRES scenario: results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the two-member ensemble medians of PRCPTOT between future climate conditions under the B1 SRES scenario (2071–2100) and recent-past climate conditions (1961–2000) in: (a) autumn; (b) winter; (c) spring and (d) annual values

Fig. A10 As Fig. 4 but for the B1 SRES scenario: results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the autumn two-member ensemble medians of each index for future climate conditions under the B1 SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD

Fig. A11 As Fig. 5 but for the B1 SRES scenario: results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the winter two-member ensemble medians of each index for future climate conditions under the B1 SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD

Fig. A12 As Fig. 6 but for the B1 SRES scenario: results of the one-sided Wilcoxon-Mann-Whitney tests for the differences in the spring two-member ensemble medians of each index for future climate conditions under the B1 SRES scenario (2071–2100) and recent-past climate conditions (1961–2000): (a) Rx5day; (b) R95T; (c) R95pTOT; (d) CDD
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Fig. A13 As Fig. 7 (right panels) but for the B1 SRES scenario: anomalies between future (2071–2100) and recent-past (1961–2000) fields in the composites of the mean sea level pressure (in hPa) within the Euro-Atlantic sector simulated by the ECHAM5 under the B1 SRES scenario in: (a) autumn; (b) winter; (c) spring. Only differences with a statistical significance level of 5% are depicted.
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Table 1. Results of the statistical tests comparing the two-member ensemble medians (M; Wilcoxon-Mann-Whitney test) and probability density functions (PDF; two-sample Kolmogorov-Smirnov test applied to the centred indices) of the CCLM-based indices with the corresponding station-based and EOBS-based indices (PRCPTOT, Rx5day, R95T, R95pTOT and CDD) for autumn in 1961–2000. Grey cells correspond to non-equality at a 1% significance level and ‘+’ (‘-’) in the tests for the two-sample medians indicates CCLM overestimation (underestimation). Data verifying the rejection of the null hypothesis are represented by S (station data) and E (EOBS dataset).

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Table 2. As in Table 1, but for winter

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Table 4. Summary of the one-sided WMW tests comparing the two-member ensemble medians of the CCLM-based indices between future and recent-past climate under the A1B and B1 emission scenarios. ‘+’ (‘-’) indicates that the median in 2071–2100 is significantly greater (smaller) than the median in 1961–2000, at a 10% significance level, in more than 1/2 grid-boxes within each region (Figs. 3–6). Mean differences between grid-box averages are also listed for statistically significant changes. Grey cells indicate that most of the grid-boxes with changes are significant at the 1% level.

<table>
<thead>
<tr>
<th>SCENARIO</th>
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<th>SEASON</th>
<th>NW of the Tejo river</th>
<th>NE of the Tejo river</th>
<th>South of the Tejo river</th>
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<td>A1B</td>
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<td></td>
<td>Annual</td>
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<td>Rx5day (mm)</td>
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<td>−11</td>
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<td></td>
<td>Winter</td>
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<td>+8</td>
<td>+6</td>
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