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Uncertainties in European summer precipitation changes: role of large scale circulation

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Abstract Climate models suggest that anthropogenic emissions are likely to induce an important drying during summer over most of Europe in the late 21st century. However, the amplitude of the associated decrease in precipitation strongly varies among the different climate models. In order to reduce this spread, it is first necessary to identify its causes and the associated physical mechanisms. Consequently, the focus of this paper is to better estimate the role of large scale circulation (LSC) in precipitation changes over Europe using a multi-model framework and then to characterize the LSC changes using the weather regime paradigm. We show that LSC changes directly lead to a decrease of precipitation over north-western Europe. This circulation-driven decrease in rainfall is mainly linked to an increase (decrease) of the occurrence of positive (negative) phase of the North Atlantic Oscillation regime. LSC is also responsible for a significant part of the models spread in precipitation changes over these regions. Over southern Europe, the role of LSC changes on multi-model mean precipitation changes is generally weak. We also show that the precipitation anomalies directly induced by LSC modifications seem to be further amplified through local feedbacks.

Keywords Regional climate · Precipitation changes · Large scale circulation · Global change

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1 Introduction

The state-of-the-art climate simulations from the world climate research programme's (WRCP) coupled model intercomparison project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007) realized in the context of the intergovernmental panel on climate changes (IPCC) assessment report 4 (AR4) have confirmed that most of Europe is likely to undergo a very strong drying during summer (Giorgi and Bi 2005; Christensen et al. 2007). Figure 1 shows that in multi-model average, summer precipitation decreases up to 0.6 mm/day over northern Spain and southern France at the end of the 21st century with the special report on emissions scenarios (SRES) A1B emission scenario.

However, the spread in the amplitude of precipitation anomalies among the different climate models is still very large, in particular over France and eastern Europe (Fig. 1) where the inter-model standard deviation is of the same order of magnitude or even greater than the absolute ensemble mean change. The summer drying over Europe might have very strong impacts and in order to take the adaptation measures needed to confront it, it is important to reduce the large associated uncertainties. As a first step, it is necessary to understand the respective roles of the different mechanisms leading to the model spread of precipitation changes in response to anthropogenic forcings. As a second step, it will be possible to evaluate the ability of the models to represent these key mechanisms, in order to improve the climate models, or to define physically-motived metric that takes into account the ability of each model to represent the key processes involved, in order to define more accurate probabilistic climate scenarios (Tebaldi and Knutti 2007).

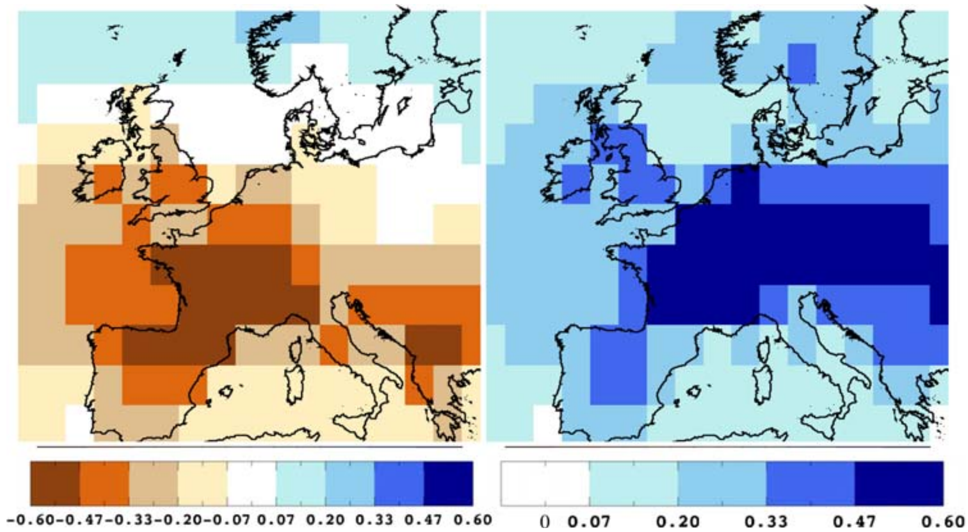

Fig. 1 (*left*) Multi-model average of precipitation changes (mm/day) between 2081–2100 and 1961–2000 in summer. (*right*) Idem for multi-model standard deviation. The same CMIP3 models described in section Models and Data are used

In this paper, we focus on the role of the changes in atmospheric large scale circulation (LSC) in precipitation changes over Europe during summer. Indeed, LSC over the North-Atlantic is a significant contributor to the daily to inter-annual variability of regional climate over western Europe. For example, the north atlantic oscillation (NAO) has important links with precipitation over Europe (Hurrell 1995). Given the strong linkages between LSC and European precipitation, it is thus worth investigating to what extent changes in LSC may explain the changes in European summer precipitation simulated by the CMIP3 models and account for the inter-model spread.

In the context of global warming, modifications of LSC may thus be an important contributor to changes in European Climate (van Ulden and van Oldenborgh 2006 for example concerning the north of Central Europe) among others, like land-atmosphere interactions (Seneviratne et al. 2006). Indeed, local processes as the soil moisture-precipitation feedbacks (Schär et al. 1999) or the increase of the land-sea thermal gradient (Sutton et al. 2007) may also lead to a decrease of precipitation during summer. The respective roles of LSC changes and the different local processes in European precipitation changes are still unclear. Rowell and Jones (2006) used an interesting experimental design to evaluate the respective role of the different physical mechanisms on future European summer drying. Their experimental design is intended to isolate four types of mechanisms that may explain summer drying in Europe: (1) reduction of moisture during spring, (2) positive soil moisture/precipitation feedback during summer, (3) large scale atmospheric changes including dynamical changes, (4) increase of the land-sea contrast leading to reduced relative humidity over the continent and thus precipitation. They use a regional climate model and represent each mechanisms using mix of inputs to the model (surface and lateral boundary data, atmospheric composition from either present and future climate). This study shows that while over United Kingdom and southern Scandinavia the changes in LSC are a major factor of summer drying, it is not the case over southern and continental Europe where the dominant mechanisms are (4) and (1). However, these results may be model-dependent, and, in particular, sensitive to the global climate model used to provide the boundary conditions: as an extreme example, if the global climate model exhibits no change in LSC, it is self-evident that the role of LSC in European precipitation changes will be evaluated as small using this methodology. This is a matter of concern because as it is shown later in this paper, the spread of LSC changes among the CMIP3 models is very large: some models exhibit no changes in LSC whereas other models show major changes. To confirm the results of Rowell and Jones (2006), it would be necessary to use the same kinds of experimental set-up in a multi-model framework.

However, this type of study is very difficult to realize in a multi-model framework. Simpler methodologies based on the available multi-model datasets are thus interesting. In this paper, the role of LSC in precipitation changes is isolated without dedicated simulations, using the available CMIP3 multi-model database. The comparison of circulation-driven precipitation changes and total precipitation changes then provides a measure of the role of the other mechanisms.

The main goal of this paper is thus to quantify and characterize the role of LSC changes in the precipitation modifications over Europe based on the WRCP CMIP3 multi-model dataset. We estimate the part of precipitation changes that directly results from LSC changes using the analog method (Zorita and von Storch 1999), applied in the model world. This methodology is designed to separate the changes that are due to the modifications of the links between the different circulation patterns and the regional climate variables from the circulation-driven changes as in Yiou et al. (2007). The weather regimes paradigm is then used to extract the physical changes of LSC. Finally, we consider the interactions between LSC changes and local processes in precipitation modifications. In particular, we show that circulation-driven precipitation anomalies may be amplified by local processes.

2 Models and data

Two sets of model integration from the CMIP3 multi-model dataset are analyzed in this paper and referred to as 20c3m for 20th century climate simulations and sreasa1b for the simulations driven by the SRES A1B emission scenario. In this paper, the 1961–2000 and 2081–2100 periods are contrasted. Given the availability of the daily variables needed for this study, 15 CMIP3 models are analyzed: (1) CGCM3.1(T63), (2) CNRM-CM3, (3) CSIRO-Mk3.0, (4) GFDL-CM2.0, (5) GFDL-CM2.1, (6) GISS-AOM, (7) FGOALS-g1.0, (8) IPSL-CM4, (9) MIROC3.2(medres), (10) ECHO-G, (11) ECHAM5/MPI-OM, (12) MRI-CGCM2.3.2, (13) CCSM3, (14) CGCM3.1(T47), (15) MIROC3.2(hires). Model references can be obtained from http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

The daily gridded precipitation observations at a 0.5 degree resolution over Europe come from the European Union Sixth Framework Program (EU-FP6) ENSEMBLES project (Haylock et al. 2007). For daily sea level pressure (SLP), the National Centers for Environmental prediction-National Center for Atmospheric Research reanalysis (hereafter NCEP) is used.

All the diagnostics shown in the following are based on summer average (June–July–August months).

3 Circulation-driven precipitation changes

3.1 Method

The change in precipitation simulated by the CMIP3 models can be schematically broken up in two parts: a part that is purely due to the changes of LSC and a part that results from the modification of the linkages between LSC and precipitation in the future climate. This second part may be due for example to the effect of local feedbacks or to changes in atmospheric water content.

The main objective of this section is to estimate the first part of precipitation change (i.e. circulation-driven change). In order to do so, for each CMIP3 model, the linkages between LSC and precipitation are first evaluated in the present climate simulation. Then, given future LSC changes and the present-day linkages between LSC and precipitation, the circulation-driven precipitation changes can be computed. This hypothetical change would result from a change in LSC while the linkages between LSC and precipitation remain identical to the present ones. In this framework, the comparison of circulation-driven precipitation changes and total precipitation changes thus provides an estimate of the role of the other (non-related to LSC) processes.

From a practical point of view, a variant of the analog method (Zorita and von Storch 1999) is used to estimate the circulation-driven precipitation changes in the CMIP3 multi-model dataset. For each day of a climate simulation (20c3m or sresa1b), we search the 30 days with the most similar circulation patterns (i.e the 30 analogs) in the corresponding 20c3m control simulation on the 1961–2000 period (note that in the classical analog method, the analogs are searched in an observed dataset and not in models outputs). Then, we compute present (future) reconstructed precipitation series given the LSC of the 20c3m (sresa1b) simulations as the average of the precipitation over the 30 analog days drawn from the 20c3m data in the two cases.

For the 20c3m simulations, when searching for the analogs of a specific day, the latter and its 15 predecessors and successors are rejected from the possible resampling set in order to avoid artificial skill.

This analysis is separately conducted for each CMIP3 model. An Euclidean distance computed on the 10 first principal components (PC) of SLP is used as the measure of similarity. The number of analogs and the spatial domain have been chosen in order to maximize the correlation over Europe between daily series of modeled and reconstructed precipitation in the control simulations. Different sensitivity experiments have been made by varying the size of the domain and the number of analogs chosen for the reconstruction. The results presented in the following are little sensitive to the number of analogs chosen, but the choice of the domain has important implications. When a very large domain is used, the explained variance of precipitation by LSC is weaker both in the present and future climate, leading to an underestimation of the role of LSC in precipitation changes. The choice of a spatial domain that maximizes the correlation between simulated and reconstructed precipitation in the present climate is thus intended to avoid to bias the estimation of the role of LSC in future precipitation changes to artificial low values.

The spatial domain encompasses Western Europe and corresponds to the spatial area displayed in Fig. 2b. In parallel, for validation purpose, the classical analog method

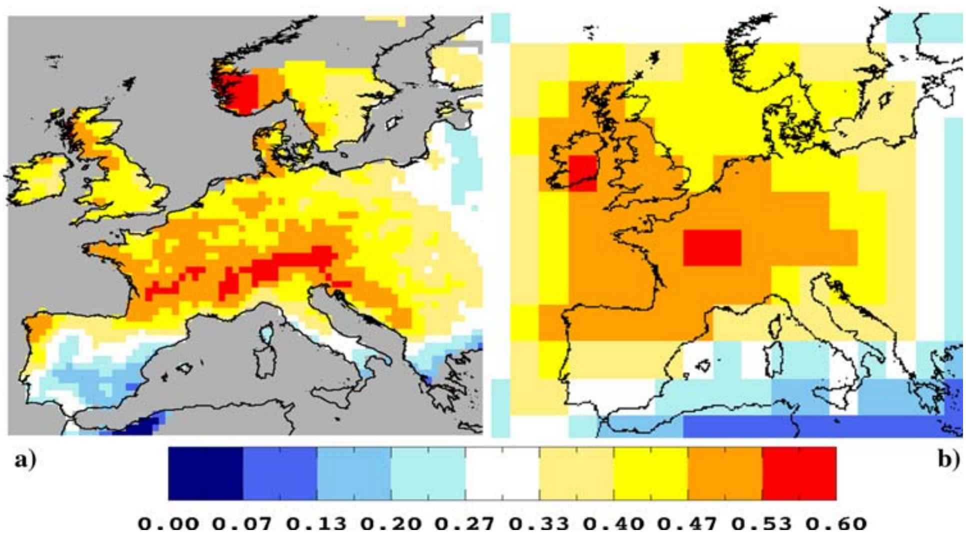

Fig. 2 **a** Daily correlation between reconstructed precipitation using NCEP SLP and observed precipitation with the analog method and observed precipitation. **b** Ensemble mean of daily correlation between reconstructed precipitation with the analog method and modeled precipitation, in the CMIP3 models

is used to similarly reconstruct observed precipitation given the NCEP SLP.

The daily correlation between reconstructed using NCEP SLP and observed precipitation is compared to the multi-model average of the daily correlation between reconstructed and modeled precipitation in the CMIP3 models (Fig. 2). Generally, the variance of precipitation explained by LSC is rather similar in the CMIP3 multi-model and in the observations, indicating the ability of the models to capture the role of LSC in European precipitation variability. Some discrepancies however exist, for example over the Alps and southwestern Scandinavia probably linked to the representation of the relief at the low resolution of most CMIP3 models. In these areas, the role of LSC on precipitation variability is underestimated. On the contrary, in other regions such as the south of England or Ireland, the role of LSC is overestimated.

3.2 Results

The multi-model mean and standard deviation of reconstructed precipitations in the CMIP3 models are then computed (Fig. 3). These results must be compared with those of Fig. 1.

The comparison of the two figures indicates that LSC changes explain a large part (comprise between 50 and 100%) of precipitation anomalies over the extreme north of France, the south of United Kingdom, Belgium, and Netherlands. By contrast, over southern Europe, the role of LSC in precipitation changes is very weak. In Spain and Greece, the LSC signal is even opposite to the total precipitation changes: LSC alone would lead to an increase of precipitation. It is thus clear from this analysis that LSC changes are unlikely to be responsible for the strong drying of the Mediterranean. LSC is also responsible for a

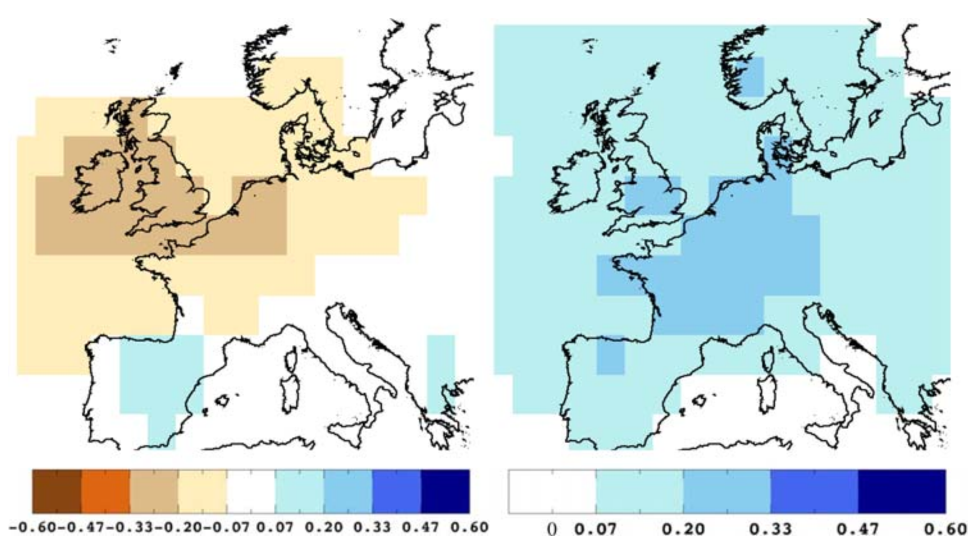

Fig. 3 (*left*) Multi-model average of circulation-driven precipitation changes (mm/day) between 2081–2100 and 1961–2000. (*right*) Idem for multi-model standard deviation

substantial part of the inter-model spread in precipitation projections over northwestern Europe countries and France, and even in areas where the role of LSC on mean changes is weak (as southern France).

Finally, the analog approach is also applied in a classical way, searching for the analogs in the observations and no longer in the control simulations: for each CMIP3 models we have searched with the same methodology as described previously the analogs in the NCEP reanalysis and taken the observed precipitation of the corresponding days for the reconstruction. This methodology allows to estimate the circulation-driven precipitation changes supposing that the links between the circulation patterns and precipitation are unbiased in the CMIP3 present climate simulations. The multi-model average and standard deviation are computed for these changes (Fig. 4).

The comparison of Figs. 3 and 4 shows the importance that the present climate biases in the representation of the links between circulation patterns and precipitation may have in future changes. Even if the spatial patterns of multi-model circulation-driven precipitation changes are rather similar when the linkages between precipitation and LSC are extracted from the 20c3m simulations or when they are extracted from the observations, a large difference in intensity exists over some areas. This difference in intensity results from the biases in the linkages between LSC and precipitation simulated by the CMIP3 models. It suggests that the CMIP3 multi-model may tend to underestimate the future precipitation decrease over most of United Kingdom, France, and western Scandinavia and Denmark.

It is also interesting to note that over Italy and southeastern Europe LSC changes alone when using the observed linkages with precipitation should lead to a small increase of precipitation that the CMIP3 models do not capture: over these areas, the CMIP3 models may thus overestimate the decrease in precipitation in the future climate. When the observed linkages between LSC and precipitation are used, an increase of the inter-model spread in circulation-driven precipitation changes over southwestern Scandinavia and the Alps is also seen (Fig. 4, right). Over these areas characterized by an important relief, the link between LSC and precipitation is generally underestimated as shown previously (Fig. 2). As a result, the spread in the changes of precipitation simulated by the CMIP3 models over these areas may be underestimated.

The results shown in this section are coherent with the conclusions of van Ulden and van Oldenborgh (2006) concerning the major role of LSC in precipitation changes in the Netherlands. Our results are also broadly coherent with those of Rowell and Jones (2006): LSC explains a large part of precipitation changes over the north of Europe, but has a weaker or even negative role concerning precipitation changes in southern Europe.

4 Weather regime analysis

4.1 Present climate

The analog approach is suitable to estimate circulation-driven precipitation changes but does not allow to describe the LSC modifications. Here, we perform a weather regime analysis to further study LSC changes in the CMIP3 models as it is powerful tool to characterize such changes.

The atmospheric circulation over the North-Atlantic can be characterized by a few number of preferred and/or recurrent quasi-stationary basin-wide pattern or weather regimes (Reinhold and Pierrehumbert 1982). In this context, the day-to-day weather fluctuations can be thought as

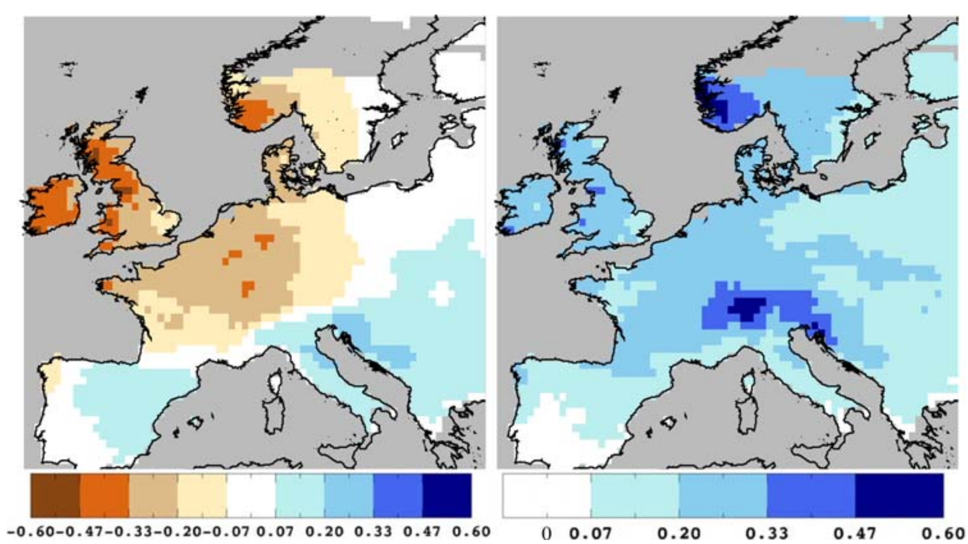

Fig. 4 (*left*) Multi-model average of circulation-driven precipitation changes (mm/day) supposing that the links between circulation patterns and precipitation in the CMIP3 models are unbiased, between 2081–2100 and 1961–2000. (*right*) Idem for multi-model standard deviation. See text for details

the temporal transition between regimes (Vautard 1990). In the context of anthropogenic climate change, a nonlinear perspective has been proposed, in which the climate system response to greenhouse forcing would be reflected by a change of the residence frequency of the system in the present-day regimes and not by the apparition of new regimes (Palmer 1999; Corti et al. 1999). However, recently, some studies have raised issues concerning the significance of the regimes obtained through classification algorithms compared to multi-normal processes and non-normal unimodal processes (Stephenson et al. 2004; Christiansen 2007). Even if these issues are very important concerning our understanding of the dynamical properties of the atmosphere, the weather regimes paradigm remains very useful to characterize LSC variability and changes, and its links with regional climate, from daily to multi-decadal time scales.

The weather regime analysis is carried out over the entire North Atlantic-European sector (20°N–80°N and 90°W–30°E) for summer days (1 June–31 August). The k-means automatic partion algorithm (Michelangeli et al. 1995) is applied to SLP daily anomalies NCEP reanalysis, in the subspace spanned by the 10 first empirical orthogonal function (EOF), over 1950–2006. The optimal partition is searched using the test proposed by Michelangeli et al. (1995) based on a classifiability index. This index is a measure of the reproductibility of the clusters when different initial seeds are used in the initialization step of the k-means partionning algorithm. The significance is assessed using a Monte-Carlo method. Here, this test leads to four regimes similarly to Cassou et al. (2005) who classified another variable (geopotential height at 500 hPa).

The second and fourth regimes can be viewed as the negative and positive phases of the summer north Atlantic oscillation (NAO) (Hurrell et al. 2003) respectively. The NAO+ regime can also be viewed as a blocking-like pattern. The links between regimes and precipitation over Europe is assessed computing the composite of observed precipitation corresponding to each regime (Fig. 5).

The NAO+ regime is characterized by high pressure centered over the British Isles and low pressure over Greenland. This pattern leads to dry conditions over Scandinavia, United Kingdom, France and wet conditions over southern Europe at the exception of western Iberian Peninsula. Opposite precipitation and pressure patterns are seen for NAO−. Although weather regimes are characterized by large scale pressure pattern, they are useful in discriminating very small scale spatial features of precipitation as it can be seen over the Iberian Peninsula. The Atlantic Low (Atl. Low) regime is characterized by a positive SLP anomaly over northern Europe and a negative anomaly over the Atlantic. This leads to warm air advection from the south and dry conditions over a large part of western Europe, at the exception of the British Isles. The Atlantic Ridge (Atl. Ridge) regime characterized by a positive SLP anomaly over the Atlantic and a negative anomaly over northern Europe, is associated to wet (dry) conditions over northern (southern) Europe. We now study the occurrence of the regimes in the CMIP3 models. SLP maps from the CMIP3 models are interpolated on NCEP reanalysis grid and then projected on the 10 leading EOF patterns of NCEP SLP. This procedure gives time series that allow to define each day of a CMIP3 model simulation in the space spanned by the 10 leading NCEP EOF. The centroids of NCEP weather regimes are then considered as reference and each day from the CMIP3 models is classified in a regime by minimization of the distance to the NCEP centroids. This procedure ensures that the reference is the same for all the models in the present and future climate, so that we can compare the occurrence of the regimes for the two periods and among the different models.

In this paper, all the days are classified in a regime, as it does not exist a perfectly objective and universal way to define the days that do not fit correctly to the clusters. However, it has been tested if the results of the study are sensitive to this choice, using the method consisting in removing the transition days between the regimes from the classification. When this method is used, the same results are obtained in terms of links between the regimes and European precipitation and changes in the residence frequencies of the regimes under anthropogenic climate change.

In the framework of this paper, the observed centroids are imposed to the CMIP3 models. This procedure is necessary in order to be able to compare the results between the different models and the different periods. However, the drawback of this method is that it is possible that the observed set of cluster is not really suitable for all the models and/or periods. In order to test if the observed clusters are relevant concerning the model states, two diagnostics are used. In a first time, the mean frequencies of occurrence of the regimes in the present climate from the CMIP3 models are compared to the observed ones (Fig. 6)

Over 1961–2000, the occurrence of NAO+ and Atl. Low is underestimated in most of models while the models generally overestimate the occurrence of NAO−. However, the errors remain small and are most of the time not significant. The very strong similarity in the frequencies of occurrence of the regimes in the models and in the observations gives some indications that the observed regimes are relevant for the CMIP3 models.

The second test consists in computing the mean Euclidean distance between the centroid and the SLP pattern of the days that belong to the regime, for each regime and model, both in the present and future climate simulations. The same distances are also computed for the NCEP

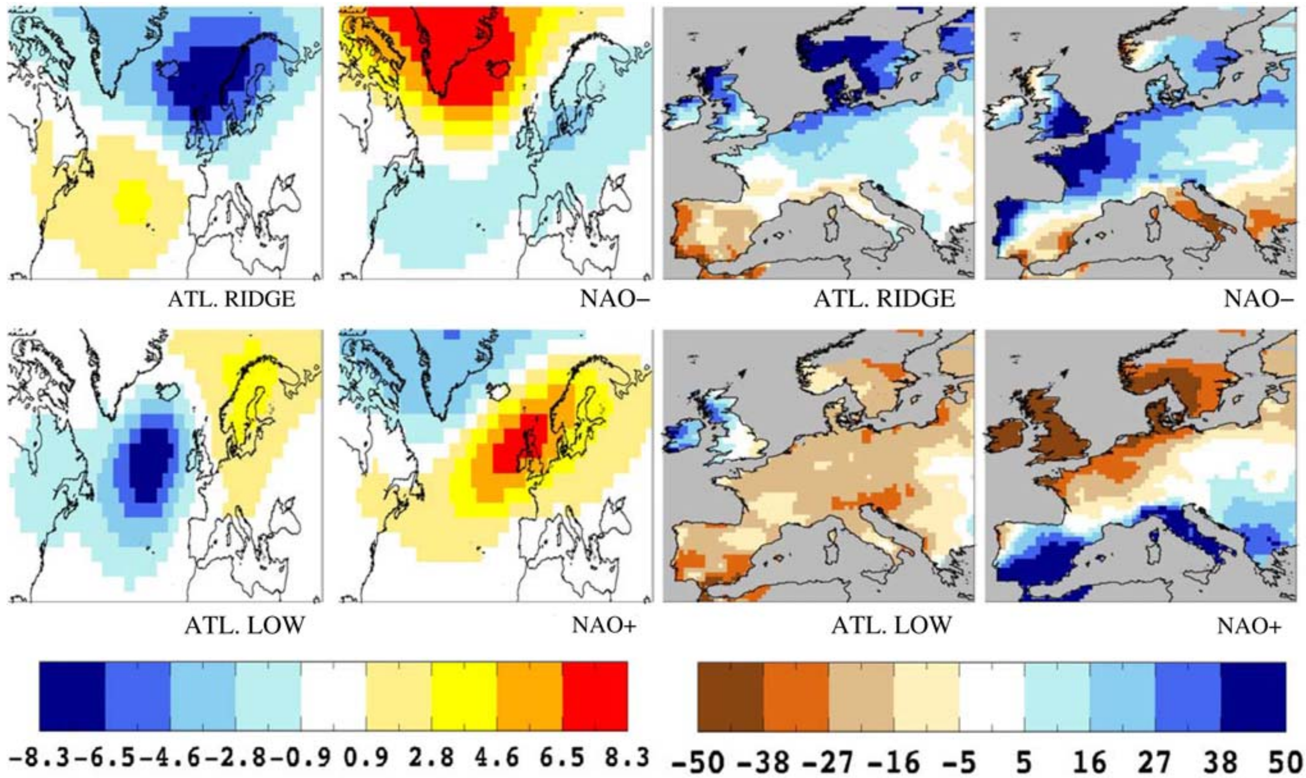

Fig. 5 (*left*) Composite anomalies of SLP corresponding to the four regimes (hPa). (*right*) Relative composite anomalies of precipitation (percentage) corresponding to the four regimes. The frequency of occurrence of the regimes is: 26% (Atl. Ridge), 23% (NAO−), 22% (Atl. Low), 29% (NAO+)

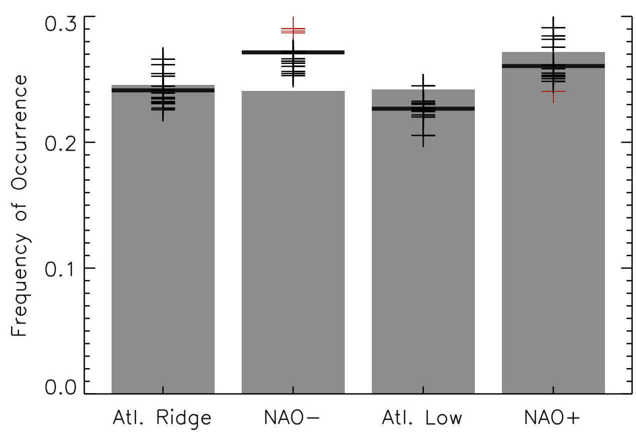

Fig. 6 Frequency of occurrence of the weather regimes in the NCEP reanalysis (*gray bars*) and in the 15 CMIP3 (*crosses*) in the 1961–2000 period. The *black line* is the CMIP3 ensemble mean. A black (*red*) cross indicates that the difference with the observed occurrence is non significant (significant) at the 0.05 level

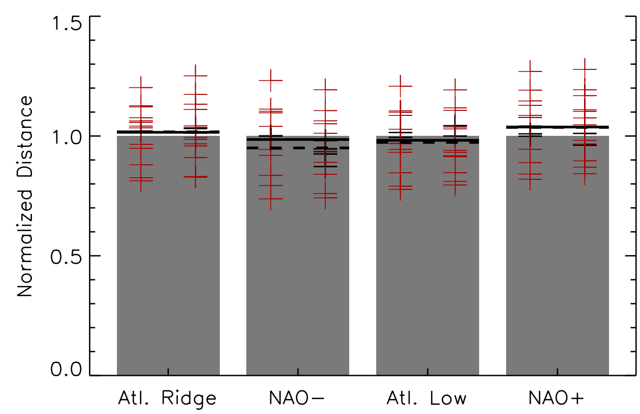

Fig. 7 Mean Euclidean distance between the SLP pattern of the days that belong to the regime and the centroid, as observed (*gray bars*) and in the present climate simulations (*crosses on the left of the bars*) and future climate simulations (*crosses on the right of the bars*). The black (*dotted*) line is the CMIP3 ensemble mean for present (future) climate. A black (*red*) cross indicates that the difference with the observed occurrence is non significant (significant) at the 0.05 level

data (Fig. 7). The comparison between the CMIP3 values and the NCEP values provides an indication about how well model days fit in observed clusters.

The mean distances to the centroid in the CMIP3 models are generally significantly different than the observed ones, even if the differences are generally small. However, the results of the CMIP3 multi-model in the present climate are very similar to the NCEP ones.

It is also interesting to note that the differences between the present and future mean distances to the centroid among the models are very limited: the states obtained in the present climate are still relevant in the future climate, which is coherent with the paradigm saying that the anthropogenic climate change may not lead to new regimes but to a change in the residence frequency in the present-days regimes.

In summary, the methodology used in this paper imposes to classify the simulated states in terms of a single set of observed regimes in order to be able to compare the results from the different models and periods. The two previous tests show that in ensemble mean, the observed clusters provide a relevant description of the model states, even if the observed partition may not be optimal for each individual model.

4.2 Future climate

We now consider the changes in the occurrence of the regimes in response to anthropogenic forcings in the CMIP3 multi-model.

Figure 8 shows the changes in the occurrence of the regimes at the end of the 21st century. In most models, an increase (decrease) of the occurrence of NAO+ and Atl. Ridge (NAO− and Atl. Low) generally occurs. However, the magnitude of these changes strongly varies among the different models. Some models exhibit large LSC changes (CNRM-CM3, GFDL-CM2.1, FGOALS-g1.0), whereas other models (MIROC3.2(medres), MRI-CGCM2.3.2) simulate very limited ones. The increase (decrease) of the occurrence of NAO+ (NAO−) corresponds to a decrease in precipitation over the north of France and United Kingdom and increase over Spain which is consistent with the pattern of circulation-driven changes seen in Fig. 2.

To confirm the role of NAO+ on precipitation anomalies, for the 15 CMIP3 models the scatter plot of the mean changes in summer precipitation over France and United

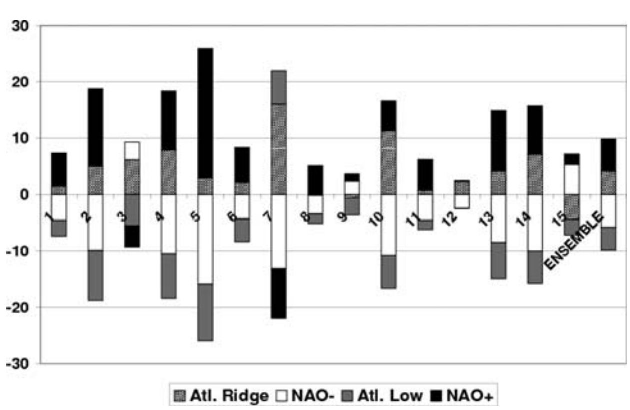

Fig. 8 Changes in the occurrences of the weather regimes between 2081–2100 and 1961–2000 (number of days during summer) in the CMIP3 models. The changes are given by the length of the shaded bar that correspond to each regimes. The number on the graph stands for the model. Ensemble refers to the ensemble mean of the CMIP3 models

Kingdom as a function of the changes of the number of days of NAO+ during summer between the two periods is shown (Fig. 9).

High correlations are obtained in the two areas: the spread in the occurrence of NAO+ seems to be responsible for a large part of the inter-model spread in precipitation.

5 Amplification mechanism

The estimate of circulation-driven precipitation changes using the analog approach in Sect. 2 is based on an implicit assumption: the changes of the links between a given circulation pattern and precipitation in the future climate are supposed to be independent from the LSC changes. However, the changes of precipitation initially due to LSC might then be amplified through local feedbacks, leading to a change of the links between circulation patterns and precipitation. For example, circulation-driven precipitation decrease may lead to lower soil-moisture, amplifying the precipitation deficit through soil-moisture precipitation feedbacks.

This example shows that the changes of the linkages between LSC and precipitation may not be independent from the changes of LSC. This kind of mechanism may lead to an amplification of the inter-model spread in precipitation changes initially caused by LSC changes. In this case, the role of LSC changes in precipitation modifications and in particular its inter-model spread may be greater than the one previously estimated using the analog approach.

Figure 10 shows for each grid point the correlation computed on the 15 values corresponding to the CMIP3 models between the total precipitation changes and the circulation driven changes computed previously with the analog method (Sect. 3). Over France, southern England and Belgium the correlation is generally greater than 0.8: the explained variance in total precipitation changes by circulation-driven precipitation changes as estimated in Sect. 3 is thus generally greater than 60% in these areas. It suggests that in the CMIP3 multi-model dataset the circulation-driven changes (ΔPanalog, estimated by the analog approach in section 3) may be a good predictor of total changes in precipitation (ΔPtotal, simulated by the models), even if their amplitudes are different. We build a simple linear regression model based on this hypothesis, assuming for each grid point that:

$$\Delta \text{Ptotal(model)} \sim \text{K}.\Delta \text{Panalog(model)} + \text{C} \quad (1)$$

The factor K can be viewed as an amplification factor of the precipitation anomalies directly caused by LSC changes. C is the constant of the regression equation, and stands for the precipitation changes that are not related to and are independent from LSC changes.

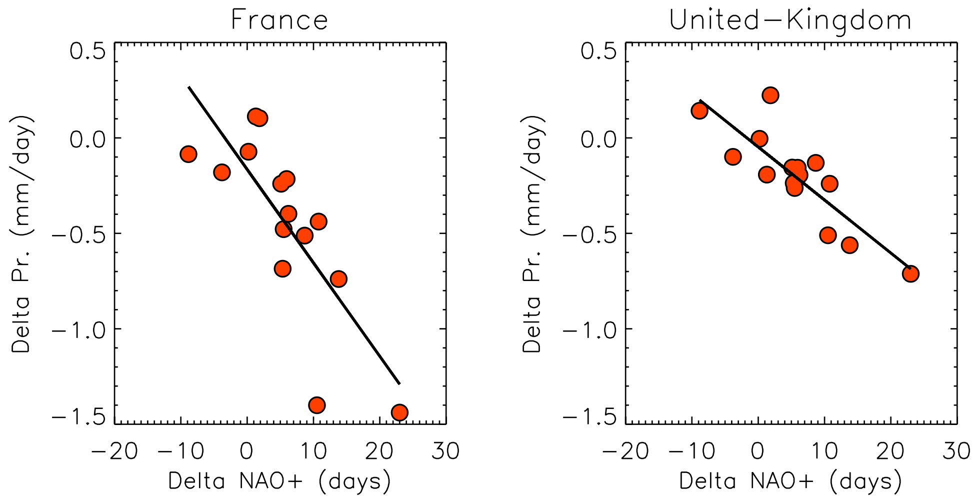

Fig. 9 (*left*) Scatter plot of the change in mean precipitation over France (mm/day) in the CMIP3 models as a function of the change in the occurrence of the NAO+ regime. The regression line is also plotted. (*right*) Idem for United-Kingdom. The linear correlation is −0.78 for France and −0.85 for United-Kingdom

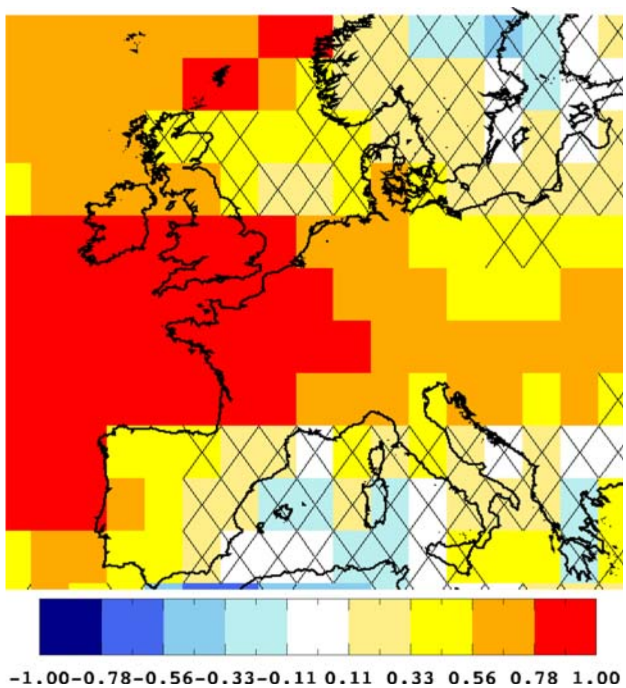

Fig. 10 Linear correlation computed across the 15 CMIP3 models values between circulation-driven precipitation changes between 2081–2100 and 1961–2000 computed with the analog approach in Sect. 3 and total precipitation changes in the same period. The *crosses* indicate the grid point where the correlation is not significant at the 0.1 level

In reality, C and K represents some physical mechanisms that are not simulated in the same way in all the CMIP3 models, and thus are not constant among the different models. Here, these variations of C and K are neglected to focus on the role of LSC in the inter-model spread of precipitation changes. As shown in Fig. 10, even if we neglect the inter-model variation in the simulation of the mechanisms represented by C and K as expressed by Eq. (1), a large part of the precipitation spread may be explained over some large areas of Europe. The value K.ΔPanalog may be considered as more representative of the real importance of LSC changes on precipitation than the sole estimate given by ΔPanalog.

The value of K.ΔPanalog is computed for each grid point and for each CMIP3 model. Figure 11 displays its multi-model mean (center panel) and standard deviation (right panel) and the value of C (left panel) It appears that in this new framework, the role of LSC changes on precipitation modification is greater than the one estimated previously using only the analog method (Fig. 3), in terms of multi-model mean and spread. It is true in particular over United Kingdom, northern France and Benelux. Through this analysis we can also see that a large part of the spread of precipitation changes among models in these areas is actually linked to the spread of LSC changes. It is also interesting to note that even if the role of LSC in multi-model mean precipitation changes over eastern Europe is very weak, LSC plays a non-negligible role in the multi-model spread over this area. The value of C, which gives a measure of the background change in precipitation independent of LSC changes in the CMIP3 multi-model, exhibits a strong south/north gradient, with positive value in northern Europe and negative value over southern Europe (Fig. 11-left). A strong land-sea contrast in C is also seen over southern Europe, indicating that land atmosphere interactions probably play an important role on this precipitation decrease not linked to LSC changes. The value of K varies between 1.3 and 2.3 where the correlation between ΔPtotal and ΔPanalog is significant (points with no cross in Fig. 10).

6 Discussion and conclusion

In this paper, the role of LSC in the changes of European summer precipitation simulated by the CMIP3 model has been studied. In particular, we have shown using the analog

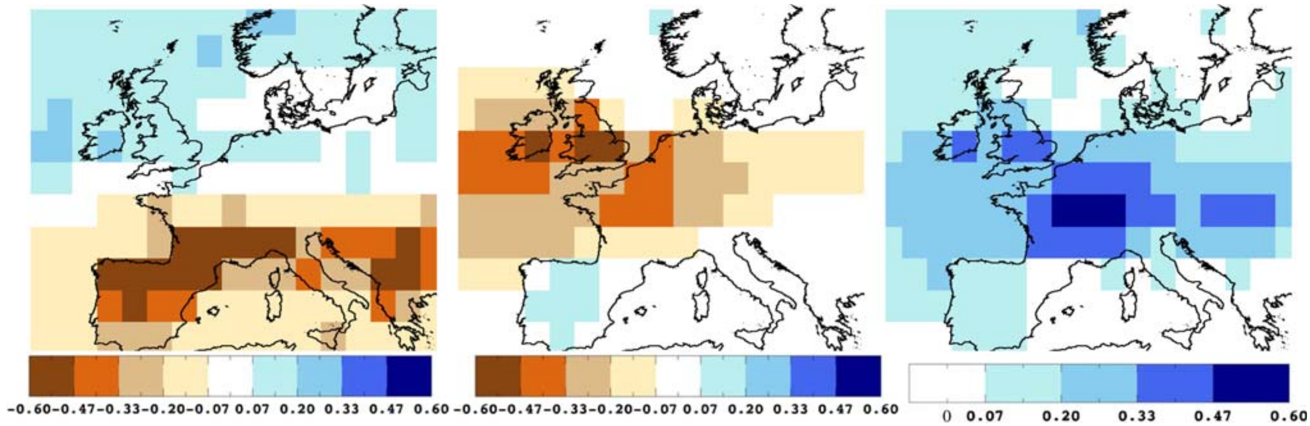

Fig. 11 (*left*) Value of C (see Eq. 1). (center) Multi-model mean and (right) standard deviation of K. ΔPanalog for the periods 2081–2100/1961–2000. See text for details

approach that the LSC is responsible for a large part of the decrease of precipitation in the north of Europe (United Kingdom, Benelux, France). The role of LSC in precipitation changes is weaker over southern Europe.

These conclusions confirm the results obtained by van Ulden and van Oldenborgh (2006) for the Netherlands based on a different methodology. Our results are also broadly coherent with those of Rowell and Jones (2006), with a large role of LSC in precipitation change in the North of Europe and a weaker or even negative role over southern and eastern Europe. However, we have shown here that even if the role of LSC changes is weak concerning the ensemble-mean precipitation changes in eastern Europe, a large part of the inter-model spread in precipitation changes over this region is actually linked to the differences in LSC changes. It is also the case in France and United Kingdom.

Circulation-driven and locally-driven regional climate variability and changes are often separated—as done here using the analog method-, in order to understand each of them more easily. We found that this partition is a simplification that may lead to an underestimation of the real role of LSC changes in the multi-model mean and spread of regional climate change. Indeed, the changes due to local feedbacks may not be independent of the changes due to LSC. Local processes may amplify the regional climate anomalies firstly caused by LSC and thus enhance the importance of model-to-model variations of LSC in regional climate changes.

A possible shortcoming of our study is that the changes in LSC might be partly driven by changes in local processes. For example Fischer et al. (2007) have shown that during the European heat wave of summer 2003, the land-atmosphere coupling may have caused a change in the atmospheric circulation over Europe. Another example concerns the role of the Mediterranean sea: Feudale and Shukla (2007) have suggested that during the European heat wave of 2003, the sea surface temperature of the Mediterranean sea amplified the atmospheric circulation anomalies over Europe. In our framework, these changes of LSC would have been detected as a cause and not as a consequence.

This problem may in particular arise with the analog approach as the chosen domain is relatively small. It is noteworthy that the regime approach, which gives coherent results with the analog approach, is based on a much larger domain, less influenced by local circulation changes. Moreover, Findell and Delworth (2005) have shown that the main driver of mean SLP change under anthropogenic forcing in their model is SST changes, and in particular SST changes in the Tropics. The role of soil moisture and land-atmosphere interactions in SLP change is comparatively very small. These results thus suggest that the possible shortcoming of our framework mentioned above is limited.

It is also important to note that in the real world the role of LSC changes could be actually greater: for example, theoretical arguments indicate that changes in the strength of the baroclinic eddies are expected in the future climate (Held 1993). These changes might not be captured correctly by some models due to their coarse resolution and in consequence by our approach.

In summary, the main conclusion of this study is the following: to improve the projections of precipitation changes over Europe (i.e. reduce the associated spread), in particular in the northern part of the continent, in response to anthropogenic forcings, it is necessary to improve the projections of LSC modifications over the North-Atlantic. In this context, it is important to note that even in areas where the role of LSC on ensemble-mean precipitation changes is weak, the LSC may still play an important role on inter-model spread: it is for example the case for eastern

Europe. It is interesting to note that the biases in the representation of the links between local precipitation over Europe and LSC lead to an underestimation (overestimation) of the precipitation decrease over northern (southern) Europe in the CMIP3 multi-model. It is an example where present climate biases can have substantial impacts on future response.

The weather regime paradigm adopted here indicates that understanding the evolution of NAO+ and NAO− events and reducing the associated spread among models is particularly crucial. As mentioned earlier, Findell and Delworth (2005) show that in their model, summer sea surface temperature changes, particularly in the Tropics, are the main drivers of mean SLP changes. It would be an interesting research direction to explore to better assess the modifications associated with NAO. It is also interesting to note that the role of LSC varies strongly over Europe: over the Iberian Peninsula, LSC changes alone in many (but not all) models would lead to an increase of precipitation whereas a decrease is actually predicted by the multimodel ensemble mean. LSC over the North-Atlantic is thus not the main driver for the strong drying over the Mediterranean. This result stresses the importance of others mechanisms over this area.

To progress on regional climate change projections over Europe, it is also important to better understand the physical mechanisms underlying the amplification processes identified in this study. The soil moisture-precipitation feedback (Schär et al. 1999) certainly plays a role but it is not the only one since an amplification is also found over the ocean.

We have also shown that even taking into account the amplification mechanism, over France and central eastern Europe which are the areas where the multi-model spread in precipitation changes is the greatest, the LSC does not account for the whole spread in precipitation. Others mechanisms, independent of LSC changes are thus important here which is coherent with the results of Boé and Terray (2008) concerning the role of the spread in evapotranspiration changes in regional climate change in these areas.

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