Testing statistical downscaling methods in simulated climates

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[1] The consistency of two statistical downscaling methods and two different predictors to estimate past (last millennium) and future (21st century) precipitation in the Iberian and Scandinavian Peninsulas is assessed in the surrogate climate of a coupled climate model simulation. The methods are based on canonical correlation analysis and the search for analogs, with sea level pressure (SLP) and 500 mb geopotential height as predictors. The precipitation downscaled by the statistical methods within the simulated climate is compared with the direct model output. The estimation based on SLP alone agrees with the modeled precipitation on the Iberian Peninsula. However, the estimates for Scandinavia in the 21st century are drier than the target precipitation. Geopotential height as predictor performs worse than SLP in both regions yielding too dry future climate. Differences in both regions are analyzed in terms of relative humidity, which contributes to future precipitation changes of Scandinavian precipitation.

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1. Introduction

[2] General circulation models (GCMs) are widely used tools to estimate future climate changes. However, the resolution of present GCMs is too coarse for many impact assessment studies. The need to provide regional information has elicited the use of different regionalization methods, which translate large-scale information to local or regional scale [*Wilby and Wigley*, 1997]. Statistical downscaling methods are based on empirical relationships between large-scale variables, which are assumed to be skillfully simulated by GCMs, and the target local variables. These relationships are then used to translate changes of the large-scale variables in terms of changes in local variables.

[3] The main underlying assumptions within these methods are: (1) the predictors are assumed to be well represented in the GCMs, (2) the relationships between the predictor and the predictand are assumed to hold in altered climates, and (3) the model calibrated with monthly to yearly variability is assumed to be applicable to mean decadal and centennial changes.

[4] Statistical downscaling methods to estimate precipitation changes have been designed in the past using, among others, sea level pressure, geopotential heights and humidities at different levels as predictors. The criterion to discriminate among the methods and predictors is usually based on the skill of the method to replicate the observed local target variable in a verification period. However, the limited length of the observational record makes difficult to validate the statistical models over longer time scales (decadal and centennial), although examples of skillful estimations of precipitation shifts have been presented [*Timbal*, 2004].

[5] The plausibility of the statistical downscaling assumptions can be more strictly tested in the surrogate world of climate simulations with state-of-the art climate models, which offer realizations of future climates and in which the target variable is known.

[6] This is the approach pursued in the present study. Here, a strict realism of the climate simulations is not required. They are considered as plausible realizations of the present and future climate evolution. Nevertheless, several studies support their ability to simulate large-scale features of present climate quite realistically [*Hanssen-Bauer and Førland*, 2001; *Nieto et al.*, 2004]. The advantage of this approach is that these surrogate climates provide us with perfect pseudo-observations of all the variables required to establish the skill of a downscaling method across time-scales. The drawback is that regional features, e.g. topography, are not well represented in the model and therefore, the estimated skill will probably be an underestimation of the skill in real circumstances.

[7] Here, the relationship to be exploited is the one between the circulation over the North Atlantic area and winter precipitation over European regions. One specific issue addressed in this study is the possible differences in the estimations of precipitation changes when two different indicators of the atmospheric circulation are used, namely sea level pressure (SLP) and 500 mb geopotential height (Z500). Although Z500 is physically more closely connected to precipitation, arguments have been proposed [*Zorita et al.*, 1995] to preferably characterize the circulation using SLP in a climate change context. A global warming signal would lead to an overall increase of Z500, but this would not be necessarily associated with a change in the circulation. A statistical model would erroneously interpret this thermal geopotential rise as a dynamic signal and lead to erroneous estimations of precipitation changes. Another question is related to the role of humidity predictors in altered climates. As mean temperature rises globally, future precipitation changes may be more strongly driven by humidity, due to the nonlinear relationship between both.

[8] Two downscaling models were tested in two different regions, the Iberian and the Scandinavian Peninsulas, located at mid and high latitudes, respectively. An opposite precipitation trend has been observed in the last 50 years, decreasing in the Iberian Peninsula and increasing in Scandinavia [*Folland et al.*, 2001]. Both regions are directly influenced by the atmospheric variability over the North Atlantic, but the main mechanisms giving rise to future precipitation changes may be different because of their latitudes. Note that the goal

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of this study is not to design the optimal downscaling method for these areas, as this optimum could be different in the real world, but to test basic assumptions made in the statistical downscaling approach.

2. Model Simulation

[9] The ECHO-G is a coupled atmosphere-ocean GCM consisting of the atmospheric model ECHAM4 (horizontal resolution approx. 3.75° × 3.75) and the oceanic component HOPE-G. The simulation covers the period 1000–2100 and was driven by estimations of past external forcing until 1990 (solar variations, greenhouse trace-gas concentrations and volcanic activity) and anthropogenic greenhouse-gas forcing according to the IPCC SRES scenario A2. In this simulation, no anthropogenic aerosols were considered [*González-Rouco et al.*, 2003, and references therein].

[10] The data selected are the monthly mean precipitation, SLP and Z500 for the months December, January and February.

[11] The area selected for the large-scale predictors for the Iberian Peninsula (see auxiliary material[1]) covers the North Atlantic sector 60°W–18.75°E, 27.5°–65°N. For the Scandinavian Peninsula the predictor area was extended to the north and east (60°W–37.5°E, 35°–88°N). These domains were selected according to several studies revealing the influence of the Atlantic circulation on climate variability over the European region [*Hurrell*, 1995]. In particular, the major circulation patterns over the Northern Hemisphere, such as the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO) or the East Atlantic pattern (EA), are captured by the selected windows.

3. Statistical Downscaling Models

[12] The period 1950–2000 was used to calibrate the SDMs. Once calibrated, the SDMs were tested by estimating the precipitation in the whole period (1000–2100) and comparing it to the ECHO-G precipitation. The SDMs are formulated in terms of detrended monthly anomalies relative to the mean of the calibration period. The results displayed in the next sections have the climatological mean added back to the estimated anomalies. The trend is recovered by applying the SDMs to the non-detrended predictor field.

[13] The SDMs, both widely used in real applications, are based on canonical correlation analysis (CCA) and analog search. The first approach is a simple linear regression based on the time coefficients obtained in a CCA decomposition [*von Storch et al.*, 1993]. The performance of this SDM is dependent on the number of empirical orthogonal functions (EOFs) retained in the CCA prefiltering and the number of CCA components used in the regression model. The *North et al.* [1982] test was used to identify non–degenerated multiplets and the stability of the patterns was determined by a Monte Carlo technique [*Cheng et al.*, 1995]. We also considered the impact of retaining one additional EOF at a time on the canonical correlations as a criterion to select the optimum number of EOFs [*von Storch*, 1995].

[14] According to those criteria, 4 principal components for SLP and Z500 and 3 for precipitation were retained over the Iberian Peninsula in the GCM simulation. The same number of EOFs were applied for the Scandinavian Peninsula, except for Z500 where 5 EOFs were considered. The selected modes are stable, non-degenerated with those rejected, and they describe more than 80% of the total variance in almost every case. The results derived from the CCA show a strong relationship between winter circulation and precipitation within the GCM. The corresponding canonical correlations obtained are generally high, (over 0.70 for the leading patterns).

[15] The analog method was selected as a simple nonlinear approach [*Zorita and von Storch*, 1999]. This technique consists of searching for the most similar pattern (the analog) in a library of large-scale predictor fields from the calibration period. The local-scale field simultaneous with the analog is the estimate of the predictand.

[16] For the analog method, the calibration period (1950–2000) was used as the analog library. However, to estimate precipitation for a year within the calibration period that year was excluded from the analog library. The weighted average of the two most similar analogs was found to be the best option for estimating the precipitation according to values of correlation and variance calculated between the downscaled precipitation and the raw model output.

4. Results

[17] The CCA patterns indicate that positive (negative) precipitation anomalies are linked to lower (higher) pressure and to lower (higher) geopotential heights in the Atlantic region northwest of the Iberian Peninsula (see supplementary information). The CCA patterns obtained for the SLP are similar to those found in observational studies [*González-Rouco et al.*, 2000] and can be explained by meridional shifts in the North Atlantic storm-tracks in this region. For instance, observed Iberian rainfall is found to be strongly anticorrelated with the North Atlantic Oscillation index, particularly in its western margin [*Hurrell*, 1995]. In Scandinavia, positive (negative) precipitation anomalies are linked to low (high) pressure and geopotential heights over higher latitudes in the North Atlantic region. Over this area precipitation is positively correlated with the North Atlantic Oscillation. Similar patterns for the SLP were also found by *Busuioc et al.* [2001] using observations.

[18] To test the performance of the SDMs we compare only the spatial average of simulated and estimated precipitation over the Iberian and Scandinavian peninsulas, respectively. The seasonal estimations are filtered by a 31-year-running mean.

[19] Over the Iberian Peninsula, ECHO-G shows rather stable precipitation during the period 1000–1990 and a decreasing future trend (Figure 1). By the end of the XXI century, the precipitation falls to around 60% of that of the last century. The SDMs using SLP as predictor are able to accurately follow the variability of the simulated precipitation during the past 1000 years and, also, the future evolution with the strong trend. For the CCA-based SDM this indicates that the linear relationship between precipitation and circulation derived at interannual timescales in the short calibration period is validated at longer timescales and in perturbed climates. A correlation analysis applied to both periods that excludes the trend of the series has shown values around 0.9

[1]Auxiliary materials are available in the HTML. doi:10.1029/2006GL027453.

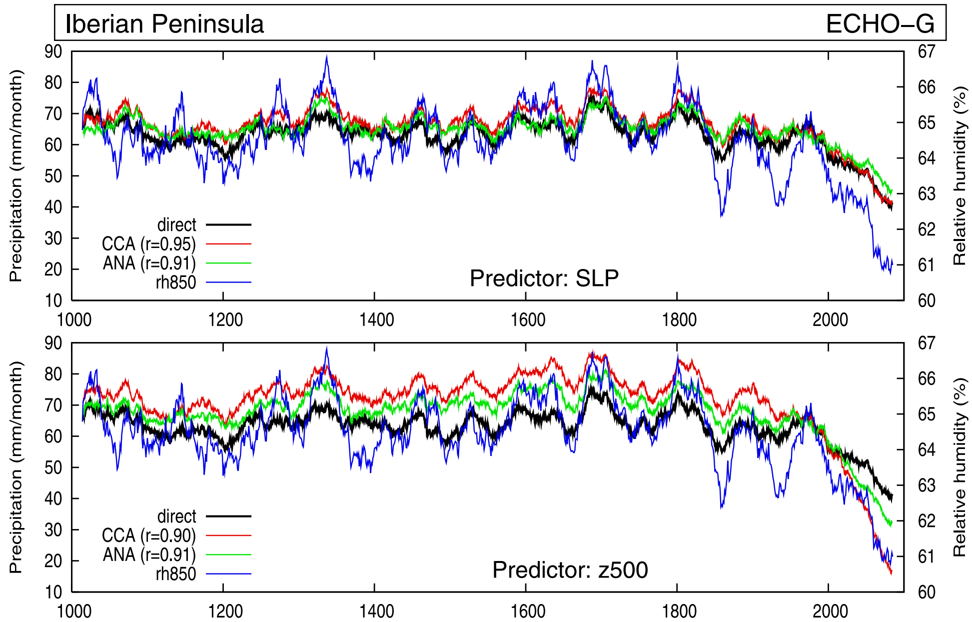

Figure 1. Winter precipitation over the Iberian Peninsula. Results from the ECHO-G direct output (black) and the estimations by the downscaling models (CCA-based SDM in red and analog-based SDM in green) using SLP (top) and Z500 (bottom) as predictors. r values denote correlation for the whole period between downscaled and ECHO-G precipitation. The area-averaged relative humidity from the model is also represented (blue).

between the estimations and the direct output precipitation, for decadally smoothed time series. For the analog-based SDM, the good performance shows that the *interannual* variations in the calibration period are large enough for good analogs to be found for future climates at *decadal* timescales. With this method the correlations with the simulated precipitation show slightly lower values in the past (around 0.8). When Z500 is used as predictor, however, a bias towards more precipitation is found in the past and clearly towards a drier climate in the future. This is likely due to the aforementioned overall change in Z500 linked to the evolution of temperatures, which is not associated with real changes in the atmospheric circulation. The global simulated temperature is colder in the past centuries than in the 20th century [*Zorita et al.*, 2004] (the so-called Little Ice Age) and Z500 tends to be lower than at present. The reverse holds for the simulated future. The SDMs erroneously translate these Z500 changes into regional precipitation changes. The CCA seems to be more sensitive to this effect than the analog method. By the end of the XXI century, a 37% (27%) decrease in the mean precipitation is estimated by the CCA (analog) method when using SLP and a 75% (53%) reduction when using Z500 as predictor.

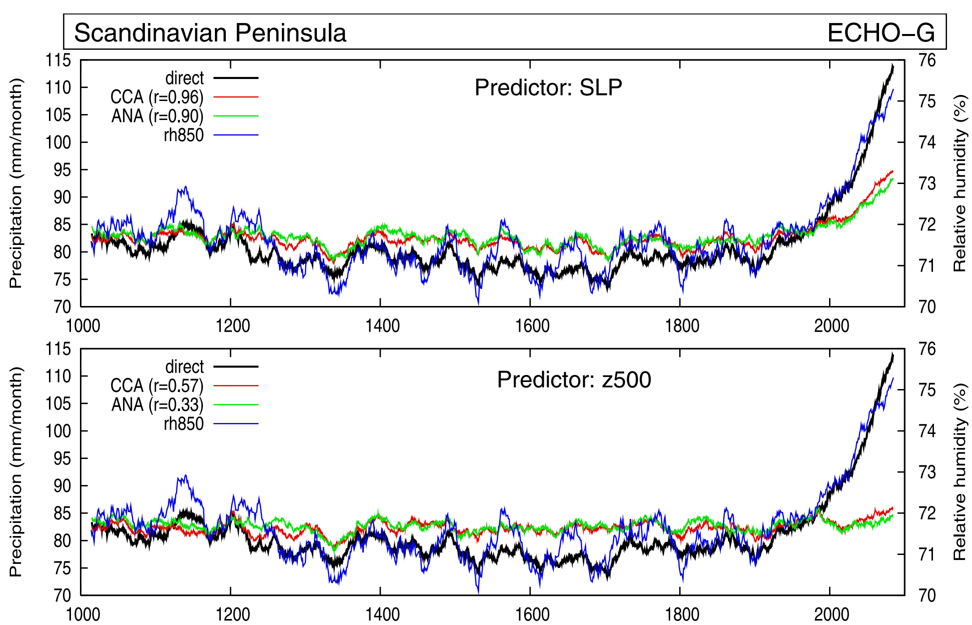

Figure 2. As in Figure 1 but for the Scandinavian Peninsula.

[20] The results for Scandinavia are shown in Figure 2. The simulated precipitation shows a small downward trend for the period 1000–1700 and an upward evolution until the end of the simulation, reaching 125% of the 1950–2000 mean. The SDMs are not able to replicate the long term trends, especially the strong positive trend in the last 100 years. In this period the SDMs driven by SLP as predictor simulate this trend better than the SDMs driven by Z500. Again, the thermal increase of Z500 is likely interpreted by the SDMs as a bias towards anticyclonic (or less cyclonic) situations, which in the calibration period are linked to drier conditions. The performance of the different downscaling methods is more similar in this area than over the Iberian Peninsula. However, the estimations show lower agreement with the simulated precipitation in the past, especially using Z500 as predictor, which results in correlations around 0.45.

[21] To understand the sources of error of the SDMs in Scandinavia, the differences between ECHO-G precipitation and estimations (residuals) have been compared with the ECHO-G series of area-averaged relative humidity at 850 mb (RH850). These residuals are found to be significantly correlated with RH850 in Scandinavia in the period 1000–1999 (to exclude the 21st century trend), approximately 0.4 at interannual timescales and 0.65 after a 31-year running mean filtering. The smoothed time series of RH850 is shown in Figure 2. It seems clear that RH850 could explain the precipitation residuals in Scandinavia in the simulated future climate as well. In our study, the downscaled precipitation only describes the precipitation more directly related to changes in the atmospheric circulation, underestimating possible variations associated with changes in the airmass characteristics. It seems that the inclusion of humidity as a predictor would improve the estimations of precipitation over this area. In contrast, in the Iberian Peninsula the residuals are not correlated with the area-averaged relative humidity. The skill of the SDMs here is already very good and these residuals probably represent just noise.

[22] There seems to be, therefore, different behavior of the factors that cause the ECHO-G precipitation changes in the Iberian Peninsula and Scandinavia. This different behavior can also be detected in the calibration period, and influences the skill of SDMs in the estimation of future precipitation changes. One possible explanation may lie in the position of both regions relative to the North Atlantic storm-tracks. The Iberian Peninsula is located at the southern fringe and any northward shift of the storm-tracks strongly affects precipitation there. In contrast, Scandinavia should be only weakly affected by shifts in the storm-track, and the imprint of variations in other factors should be clearer.

[23] Similar conclusions have been reached in a simulation with the HadCM3 model driven by the same future scenario of trace gas atmospheric concentrations for the past and present century. These results will be presented in a more detailed forthcoming study.

5. Conclusions

[24] 1. The two statistical methods to downscale seasonal winter precipitation, (linear and non-linear), tested in the surrogate climate of a GCM in two climatically different regions, yielded quite similar results, and the differences were mostly due to the use of different predictors rather than to the method.

[25] 2. The use of Z500 as predictor introduces an unrealistic bias, probably associated with temperature changes, in the downscaled precipitation. The CCA method is more sensitive to this artificial signal. Difference in skill was found between the linear and non-linear SDMs.

[26] 3. For the Iberian Peninsula, SLP is a sufficient predictor and humidity adds no additional information to improve the estimation skill of the statistical methods for future climate. However, in Scandinavia, SLP is clearly insufficient. The errors of the rainfall estimations are strongly correlated with area-averaged relative humidity in this region, suggesting that this predictor should also be included in statistical downscaling in the real world. A systematic analysis could help determine whether this difference between mid and high latitude regions can be generalized.

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