Downscaling of Global Climate Change Estimates to Regional Scales: An Application to Iberian Rainfall in Wintertime

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ABSTRACT

A statistical strategy to deduct regional-scale features from climate general circulation model (GCM) simulations has been designed and tested. The main idea is to interrelate the characteristic patterns of observed simultaneous variations of *regional* climate parameters and of *large-scale* atmospheric flow using the canonical correlation technique.

The large-scale North Atlantic sea level pressure (SLP) is related to the regional, variable, winter (DJF) mean Iberian Peninsula rainfall. The skill of the resulting statistical model is shown by reproducing, to a good approximation, the winter mean Iberian rainfall from 1900 to present from the observed North Atlantic mean SLP distributions. It is shown that this observed relationship between these two variables is not well reproduced in the output of a general circulation model (GCM).

The implications for Iberian rainfall changes as the response to increasing atmospheric greenhouse-gas concentrations simulated by two GCM experiments are examined with the proposed statistical model. In an instantaneous "2 CO_2" doubling experiment, using the simulated change of the mean North Atlantic SLP field to predict Iberian rainfall yields, there is an insignificant increase of area-averaged rainfall of 1 mm/month, with maximum values of 4 mm/month in the northwest of the peninsula. In contrast, for the four GCM grid points representing the Iberian Peninsula, the change is −10 mm/month, with a minimum of −19 mm/month in the southwest. In the second experiment, with the IPCC scenario A ("business as usual") increase of CO_2, the statistical-model results partially differ from the directly simulated rainfall changes: in the experimental range of 100 years, the area-averaged rainfall decreases by 7 mm/month (statistical model), and by 9 mm/month (GCM); at the same time the amplitude of the interdecadal variability is quite different.

1. Introduction

General circulation models (GCMS) are widely used to assess the impact that an increased loading of the atmosphere with greenhouse gases might have on the climate system. One major problem concerning numerical experiments involving GCMs is related to the horizontal resolution of the models: The following notation for the horizontal spatial scales can be adapted: the *minimum scale* is defined as the distance between two neighboring grid points of the GCM, whereas the *skillful scale* is larger than N gridpoint distances. It is likely that $N \geqslant 8$ (Grotch and MacCracken 1991). Scales larger than the skillful scale are denoted as *large scales,* and scales below the skillful scale are *regional scales.* In most climate models, the minimum scale is of the order of 500 km, so that their regional scales are of ≤2000–4000 km.

It is widely accepted that present-day GCMs are able to simulate the large-scale atmospheric state in a generally realistic manner, and it is believed that these models are the adequate tool to predict large-scale climate changes. Even though GCMs produce values on the minimum scale, their implications on regional climate are questionable.

The idea of large-scale reliability is illustrated in Fig. 1, showing the observed long-term mean (1950–1979) rainfall distribution (Shea 1986) and that which is simulated by the ECHAM model (Roeckner 1989). Global features, such as the rainbands marking the intertropical convergence zones (ITCZs), the tropical rainfall areas over the continents, and the subtropical deserts, are generally well simulated. A discrepancy is observed in the eastern and central tropical Pacific, where a marked rainfall maximum is missed by the model. At midlatitudes the storm-track areas of enhanced rainfall are correctly simulated even if the noisy character of precipitation patterns prevents a detailed comparison between model and observations. The model's limitation with respect to the regional scale are illustrated in Fig. 2, which shows the annual cycle of the mean observed and simulated rainfall on the Iberian Peninsula [the GCM data are based on four grid points (see Fig. 9b), and the observed numbers are averages of 29 stations (see Fig. 3b)]. Certainly,

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part of the discrepancy is also due to deficiencies and the irregular distribution of the observing network.

Many customers of climate-change forecasts, such as hydrologists, request information on the regional scale. An additional problem is that the demanded information, for example, local rainfall, is dependent on subgrid-scale processes. These subgrid-scale processes are taken into account in GCMs by means of *param-*

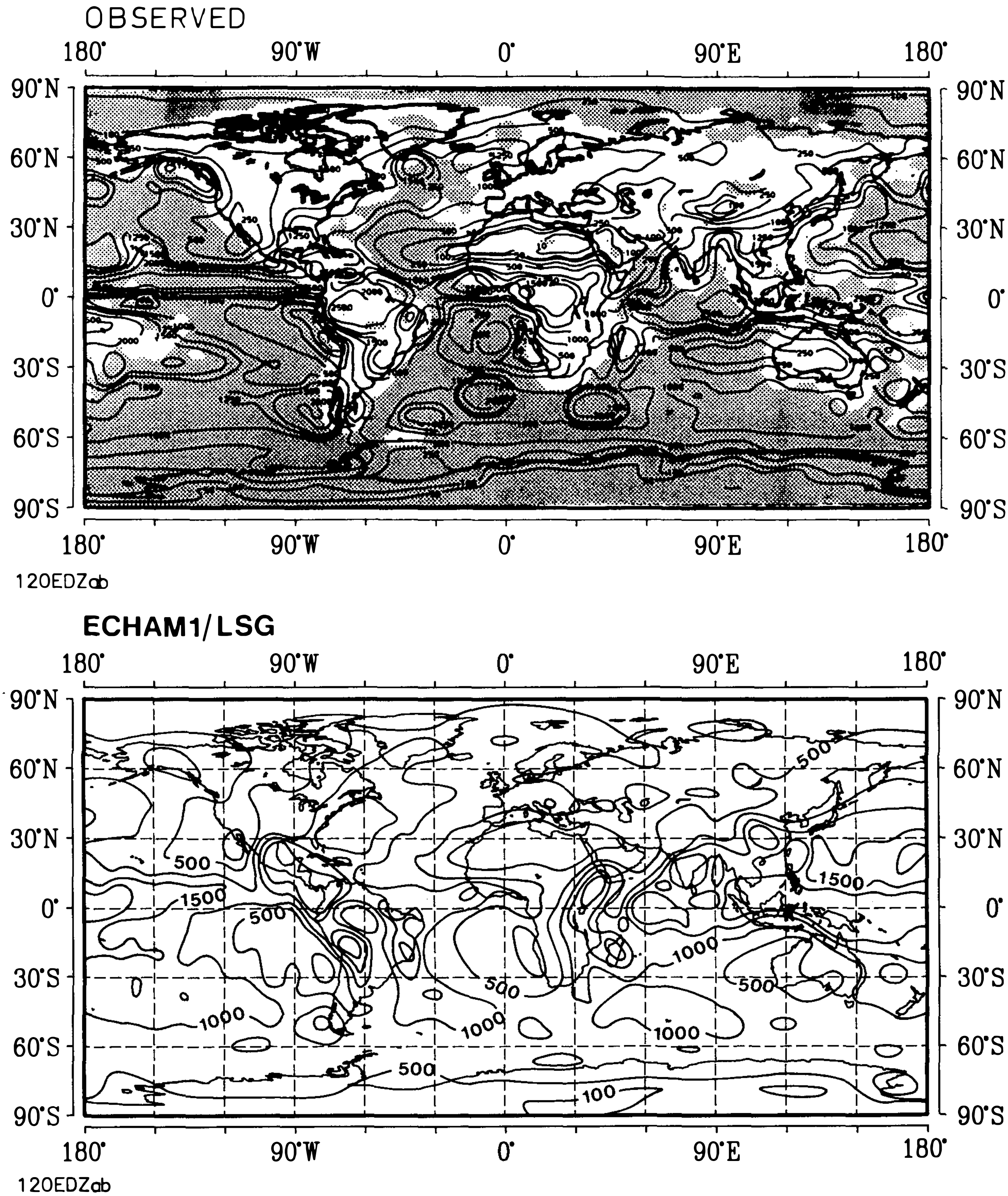


FIG. 1. Annual mean precipitation (mm/year) derived from observations (Shea 1986) and from the control "1 CO_2" run (ECHAM1/LSG coupled GCM).

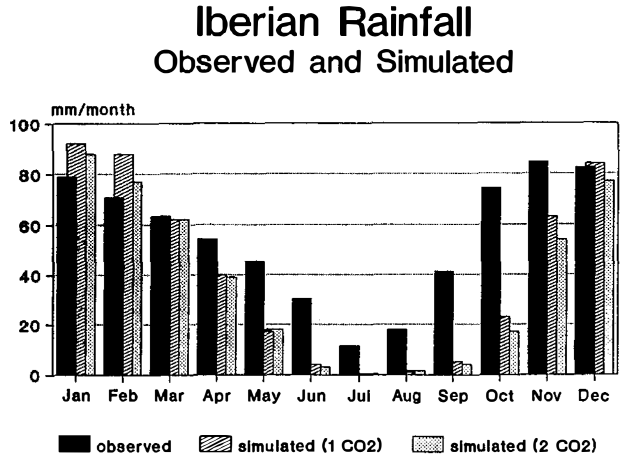


FIG. 2. Mean annual cycle of precipitation averaged over the Iberian peninsula (mm/month) derived from the observations, from the GCM control run and from the GCM "2 CO_2" experiment. The observed data are derived from 29 stations included in the WMSC dataset. The GCM data are averages of four grid points roughly coincident with the Iberian Peninsula (for their locations, see Fig. 9b).

eterizations, that is, by semiempirical methods that are "tuned" to reproduce the net effect of the considered process on the global-scale flow. The parameters are often derived from data obtained in regional experiments, but the resulting approximations are then used everywhere on the globe. Clearly, this procedure yields less reliably simulated local numbers.

All possible strategies to gain estimates of regional-scale climate changes are based on the belief that the GCMs yield a reliable estimate on the large scale. An inadequate, but often used, strategy is to believe in the time series simulated at individual grid points and to simply interpolate the coarse grid data to a finer grid (Cohen and Allsopp 1988; Smith 1991). A reasonable strategy is to trust the predicted large-scale changes and, whenever possible, to infer regional changes by means of sensibly projecting the large-scale information on the regional scale. This projection may be done with a limited-area model of the considered region (Giorgi 1990). An alternative approach is to apply empirically derived relationships between regional climate and large-scale flow. For this mixed empirical dynamic to be useful two conditions have to be fulfilled: first, the statistical connection between large-scale flow and regional climate should explain a great part of the observed variability of the regional variable, and second, the expected changes in the mean climate should lie within the range of its natural variability, so that all possible climates, sufficiently near the present one, have been visited in the past.

Pursuing the latter approach in the present paper, we present an example by considering the winter (DJF) precipitation on the Iberian Peninsula. In a previous paper, Zorita et al. (1992; referred to as ZKS in the following) showed by means of canonical correlation analysis (CCA) that there is a strong statistical relationship between Iberian Peninsula winter-rainfall anomalies and North Atlantic sea level pressure (SLP) field anomalies. One pair of canonical correlation patterns describes a significant percentage of Iberian DJF-rainfall variability (65%) and of North Atlantic SLP variability (40%) (see section 2). Formally similar procedures have been proposed by Wigley et al. (1990) and Karl et al. (1990). However, these procedures do not operate on *large* scales. Instead, they try to exploit the GCM minimum scale (i.e., grid point) information to derive subgrid-scale information.

After a brief summary of the ZKS results the proposed statistical scheme is tested by applying it to the time series of DJF mean sea level pressure distributions and Iberian rainfalls in this century (section 2). In section 3 the statistical scheme is used to derive Iberian rainfall changes from the atmospheric flow changes simulated in two experiments conducted with the ECHAM1/large-scale geostrophic (LSG) model. In one experiment, the concentration of CO_2 is suddenly increasing from the beginning, and in the second, the concentration is continuously increased according to one of the projections of the Intergovernmental Panel on Climate Change (IPCC, scenario A). These indirectly derived rainfall changes are compared with the changes directly calculated by the GCM. The paper is concluded with a discussion in section 4.

2. The statistical model for the inference of regional scale anomalies from large-scale anomalies

In this section, first specified is the statistical model that relates the irregularly distributed Iberian Peninsula (Spain and Portugal) rainfall field to the gridded observed sea level pressure field in the Atlantic Sector. The analysis is limited to northern winter, which is the season with maximum rainfall on the Iberian Peninsula (see Fig. 2). Then, DJF Iberian rainfall anomalies for the period 1900 to 1980 are estimated from the SLP fields using the resulting statistical model and are compared with in situ observations.

a. *Specification of the statistical model*

ZKS used canonical correlation analysis (CCA; e.g., Barnett and Preisendorfer 1987) to describe the coherent simultaneous variations of Iberian rainfall and of the North Atlantic SLP field in winter. ZKS analyzed seasonal mean rainfall from 29 stations [from the World Meteorological Station Climatology (WMSC) dataset] and North Atlantic sea level pressure (from the Comprehensive Ocean Atmosphere Data Set, COADS) in the period 1950–80, and found one dominant pair of patterns. The SLP pattern (Fig. 3a) is essentially composed of the leading EOF of the winter SLP field in the North Atlantic sector. The rainfall pattern (Fig. 3b), which accounts for 65% of the total interannual variance, indicates that maximum anom-

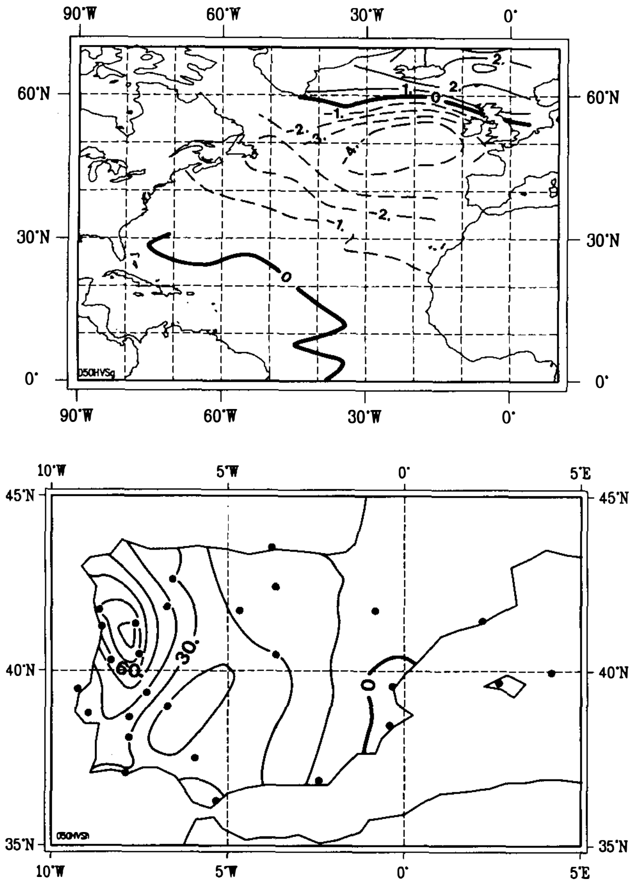


FIG. 3. Canonical correlation patterns of observed winter (DJF) Iberian rainfall and simultaneous SLP field in the North Atlantic area. These patterns explain about 65% and 40% of the respective total variances. The correlation between the respective amplitude time series of these patterns is 0.75. According to canonical-correlation analysis this is the highest correlation possible for any pair of patterns. The SLP data (mb) are derived from COADS on a 10° × 4° lat-long grid from 1950 through 1980. The rainfall data (mm/month) comprise 29 stations, the locations of which are marked by dots, from WMSC covering the same period.

alies of Iberian rainfall associated with the SLP field take place in the western part of the peninsula, and that anomalies in the southeast part are small. Similar relationships between the SLP field and rainfall in North Africa have been reported by Lamb and Peppler (1987).

The two patterns represent a reasonable physical relationship: if the sea level pressure pattern (Fig. 3a) has a positive coefficient then the mean advection of maritime air from the ocean to the Iberian Peninsula is intensified. The process of lifting humid air at the coastal mountains of the Peninsula is more efficient than on average, and rainfall is enhanced. If the coefficient is negative, the mean advection is weakened and, consistently, less rainfall is happening. Since it is unlikely that the regional rainfall anomalies drive the large-scale Atlantic sea level pressure distribution, ZKS concluded that, on the seasonal time scale, Iberian precipitation is mostly controlled by the SLP field. This is the rationale for using the canonical correlation SLP pattern (Fig. 3a) and its associated time series as a predictor of the Iberian rainfall anomalies.

We use ZKS's CCA to construct a simple statistical-regression model to relate Iberian rainfall and North Atlantic SLP. Denote $\mathcal{S}$ and $\mathcal{R}$ the two canonical correlation patterns for SLP and rainfall (Fig. 3), respectively. The SLP and rainfall signals that evolve coherently are the patterns $\mathcal{S}$ and $\mathcal{R}$ modulated by the time-dependent amplitudes $s(t)$ and $r(t)$, which, as result of the CCA, are optimally correlated. This means that once the value of $s(t)$ at a particular time is known, an estimation of $r(t)$ is possible using the simple regression relationship between both time series. The coefficient $s(t)$ for a particular distribution of SLP anomalies is obtained as the dot product $s(t) = S(t) \cdot \mathcal{S}^*$ of the SLP anomaly field $S(t)$, at time t, with the adjoint CCA pattern $\mathcal{S}^*$. Then, the best estimation of the rainfall pattern amplitude $r(t)$ is given by:

$$r(t) = \alpha s(t) \tag{1}$$

and, therefore, the rainfall signal for that particular time is

$$\hat{R}(t) = \hat{r}(t)\mathcal{R} = \alpha \cdot s(t) \cdot \mathcal{R}. \tag{2}$$

The regression coefficient α is given by $\alpha = \rho_{sr} \cdot (\sigma_r / \sigma_s)$, with σ_r and σ_s being the standard deviations of $s(t)$ and $r(t)$ and ρ_{sr} the correlation between them.

If we regard the SLP coefficient $s(t)$ as an approximate index of the strength of the westerly advection in this region, the regression (2) linearly relates an anomaly in this strength, excited either by natural low-frequency variability or by anthropogenic climate changes, to simultaneous Iberian rainfall anomalies. Only the proportion (65%) of seasonal rainfall variability that can be traced to changes in the SLP field is described in this procedure. A natural question is whether there are other large-scale processes that might be used to specify the remaining 35% of Iberian rainfall variance. According to ZKS the obvious candidate, North Atlantic SST, may be dismissed. North Atlantic SLP interannual variability controls both the Iberian rainfall and the North Atlantic SST anomalies. Remote effects exited by variations in the strength of the Hadley cell could also contribute to seasonal variations of Iberian rainfall. Lack of adequate data prevents us from quantifying this possible link. Part of the regional rainfall is due to more erratic regional processes (for example, local soil-moisture feedback) so that a complete (100%) specification of seasonal rainfall is unlikely. It may be possible that these or other factors become more important in determining Iberian rainfall in a new climate. In the context of this statistical approach, however, it is assumed that the internal variability of the climate has already produced situations in the past in which all these factors have varied in a more or less random manner. The CCA indicates that through the analyzed period, the influence of the Atlantic SLP field has been the most important. Therefore, it is likely that Iberian rainfall will be more sensitive to SLP changes in the new climate than to any other factor. This will be checked in the next section.

b. Reconstruction of Iberian DJF rainfall anomalies 1900–1986

According to observations sea surface temperatures in the Atlantic Ocean have undergone considerable variations in this century (Hense et al. 1990). In particular, the SST in the decades 1904–13 and 1951–60 exhibited strong differences. Correspondingly large variations of North Atlantic SLP were also observed during these periods. The difference field between the 1903–14 mean SLP field and the 1951–60 mean SLP field (from the National Center for Atmospheric Research analysis that contain fewer missing values than the COADS in the early years of the century) is shown in Fig. 4. Hense et al. (1990) confirmed, through a series of GCM sensitivity experiments, that the SST and SLP changes were consistent, and concluded that the interdecadal variations were real and not artifacts of changing observation procedures.

The varying atmospheric circulation over the Atlantic Ocean provides the opportunity to test the reliability of our statistical procedure to diagnose Iberian rainfall anomalies. To accomplish this, SLP anomalies $S(t)$ were derived for each DJF season between $t = 1900$ and $t = 1980$ (also from the National Center for Atmospheric Research analysis). The respective consistent rainfall anomalies $\hat{R}(t)$ were estimated with the regression formula (2). The estimates, $\hat{R}$, were verified with in situ observations from an Iberian rainfall dataset compiled by E. Zurita (1993, personal communication) for 30 Spanish stations. The WMSC dataset could not be used because it contained only two stations with a long enough record. To avoid inconsistencies we are considering only those stations that are contained in both the "Complutense" dataset and in the WMSC dataset.

First, the difference between the two decades 1904–13 and 1951–60 is addressed. In Fig. 4a, the North Atlantic SLP difference field is shown. In the early part of the twentieth century, the westerly wind was shifted northward compared to the 1951–60 decade, so that, likely, less baroclinic disturbances were traveling to the Iberian Peninsula than in the middle of the century. Consistently, the estimated and observed DJF mean precipitation differences, $\hat{R}(1904\text{–}13)\text{–}\hat{R}(1951\text{–}60)$ and $R(1904\text{–}13)\text{–}R(1951\text{–}60)$, at the 12 joint Complutense/WMSC stations are all negative (Fig. 4b). Apart from Badajoz, the sign of the estimated and observed anomalies coincides in all stations. At some locations, such as Madrid, Valencia, and Burgos, the coincidence is very good, but at Coruña the observed change is fivefold the estimated signal. In ten stations the estimated differences are smaller than the observed ones, and this is likely due to a deficiency in the statistical model in the first third of the century (see following paragraph).

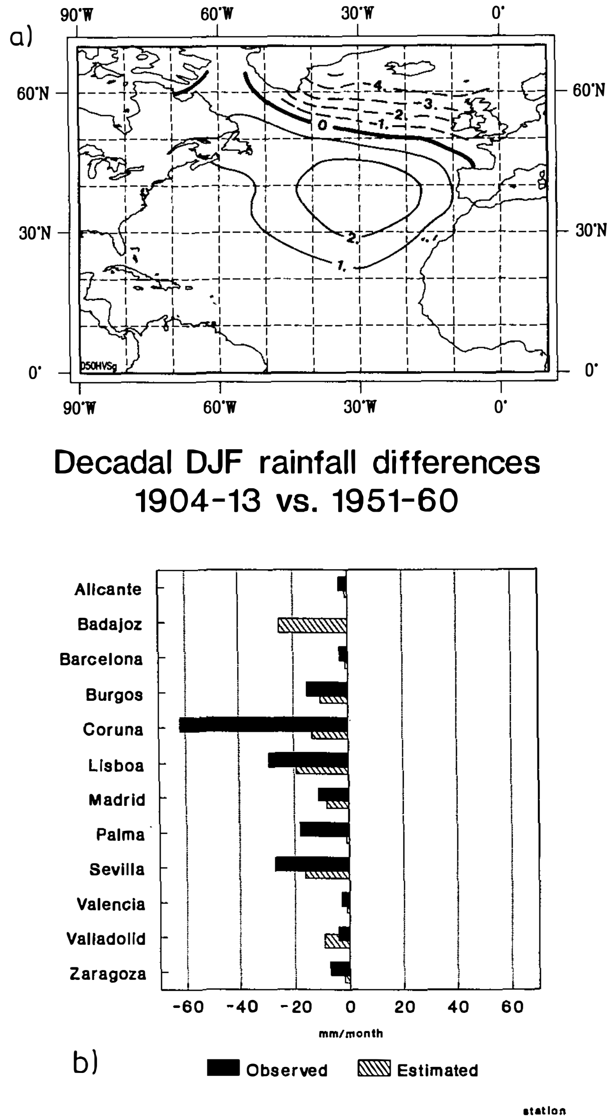


FIG. 4. Interdecadal DJF differences between 1904–13 and 1951–60. (a) Winter mean SLP difference (mb), derived from the NCAR analysis; (b) winter precipitation differences (mm/month) at the 12 stations contained in both the Complutense dataset and in the WMSC dataset. Solid: in situ observations; hatched: rainfall difference estimated from the SLP difference shown in (a).

In Fig. 5 we show the temporal evolution (5-year-running mean) of the spatial averages of the estimated and of the observed winter precipitation for the 12 joint Complutense/WMSC stations. The variations in both curves are, on all resolved time scales, highly coherent, with an overall correlation of 0.70 after trend correction. A discrepancy is found in the period between 1910 and 1930 when the statistical model slightly overestimates the precipitation. Interestingly, both curves exhibit coherent long-term variations. Spectral analysis of the unfiltered data (not shown) reveals that these

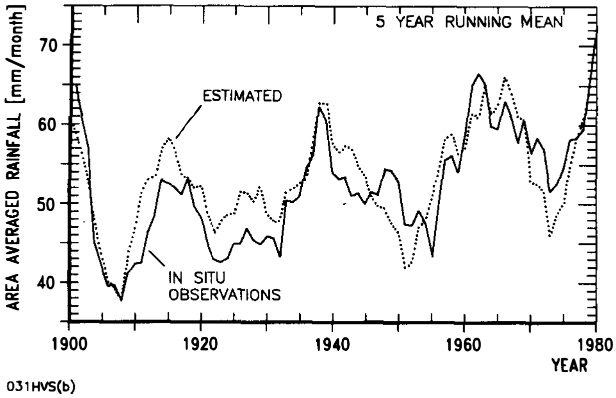


FIG. 5. Five-year-running mean time series of area-averaged winter (DJF) mean rainfall (mm/month) as derived from station data and as derived indirectly from the state of the North Atlantic SLP field. Because of lacking data in the WMSC dataset in the early part of the century, not the WMSC stations but those with a complete record, from 1900–1980 in the Universidad Complutense station dataset, have been used.

coherent variations primarily stem from the 20-year and 8-year time scales. Parallel upward trends of about 10 mm/month in 80 years [corresponding to about 0.1 (mm/month)/year] are also observed in both curves. Since the two curves in Fig. 5 originate from totally independent sources, we conclude that the trend as well as the long-term oscillations are real.

Several hypotheses have been put forward regarding the origin of the low-frequency variations of the North Atlantic SLP field [Ikeda (1989) and references therein]. The mechanism responsible for the trend is, however, unknown.

3. GCM experiments

In this study we examine two extended-range experiments with a coupled atmosphere–ocean GCM that were carried out at the Max-Planck-Institut für Meteorologie in Hamburg (Cubasch et al. 1992). The atmospheric GCM (ECHAM1) is a low-resolution version (T21L19) of the ECMWF model adopted in Hamburg for climate studies (Roeckner et al. 1989). The ocean GCM is a "Large-Scale-Geostrophic (LSG) model" (Mikolajewicz and Maier-Reimer 1990) with the same horizontal resolution as the atmosphere model (about 5.6°) and 11 layers in the vertical. It includes a thermodynamic ice model. Both models are coupled synchronously with a time step of 1 day.

Two experiments done with this model will be evaluated here: the first experiment, named "2 CO_2," assumes an instantaneous increase of the present greenhouse-gas level to 720 ppm CO_2 equivalents. In the second experiment, "Scenario A," a continuously increasing greenhouse-gas concentration is specified according to the IPCC scenario A ("business as usual") (Houghton et al. 1990). Both experiments have been run for a period of 100 years and will be compared against a 100-year "control" integration, that is, an experiment run with the a greenhouse-gas concentration set at 390 ppm CO_2 equivalents.

In this section we describe the model's ability to simulate the observed climate by examining the control run on regional and larger scales. Then, the climate-change experiments are analyzed with respect to the Iberian rainfall.

a. Control run

The following description is based on the long-term means estimated using the last 80 years of integrations that appear to be quasi-stationary.

The favorable performance of the model on the global-scale has already been demonstrated in Fig. 1, showing the annual mean precipitation field as observed and as simulated.

In Figs. 2 and 6 we show the annual cycles of the area-averaged Iberian rainfall, sea level pressure, and

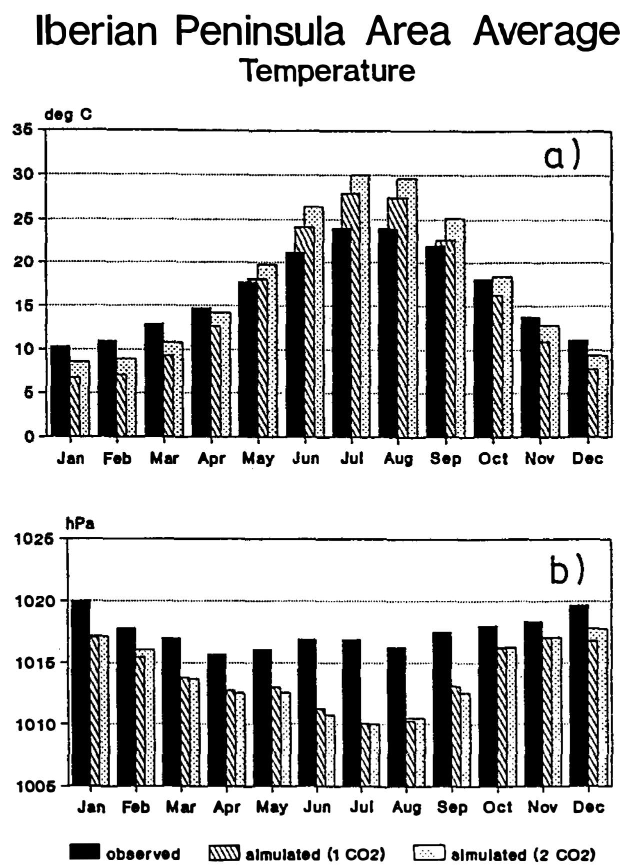
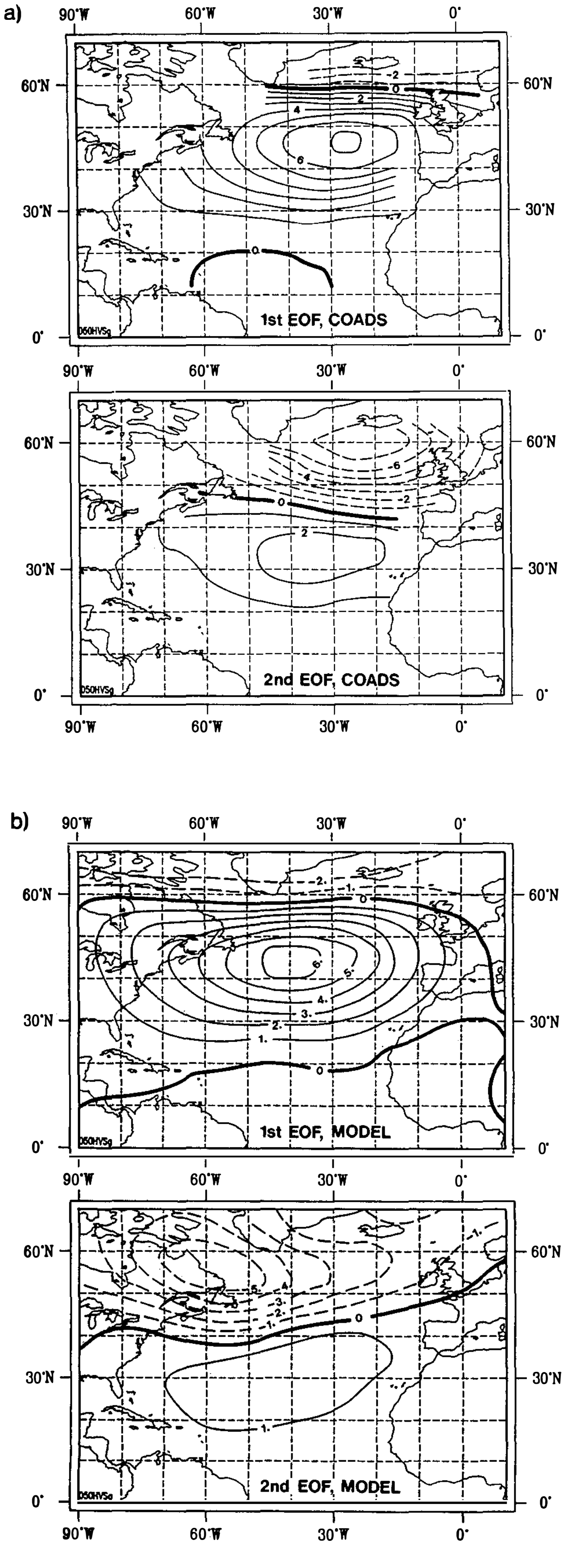


FIG. 6. Annual cycles of the area-averaged long-term means of Iberian Peninsula surface air temperature and sea level pressure. The observed values (solid bar) are derived from the 29 WMSC stations irregularly distributed on the peninsula; the values simulated in the control run and in the CO_2 experiment represent the mean over the four grid points shown in Fig. 9b. (a) Interannual means of surface air temperature (°C); (b) interannual means of sea level pressure (mb).



2-m temperature. The GCM figures represent the mean of the four grid points that are roughly located in the Iberian Peninsula (for their locations see Fig. 9b). The "observed" curves have been derived from the 1950–80 reports of the 29 WMSC stations.

The forms of the annual cycles of rainfall, sea level pressure, and 2-m temperature in the simulated data roughly agree with observations (Figs. 2 and 6). There are, however, major differences with respect to details. The modeled SLP is too low throughout the year, and the amplitude of the seasonal cycle is overestimated. Temperature is underestimated in winter and overestimated in summer so that the annual temperature range is too large in the GCM. The winter rainfall, which is mostly due to baroclinic disturbances migrating from the Atlantic Ocean to the Peninsula, is overestimated in the model. In summer, when rainfall is primarily caused by local storms, the model is too dry.

An important aspect that is relevant in this context is the interannual variability of the North Atlantic SLP in wintertime. Figure 7 shows the first two empirical orthogonal functions (EOF) of the observed and simulated DJF SLP variability in the North Atlantic. They are all of large scale, and the first observed pattern (explaining 38% of the variance) is similar to the first simulated (27%); and the second observed pattern (29%) resembles, although not so closely, the second simulated (31%). We conclude that our basic assumption, namely that the GCM is doing a credible job on the large scale is justified, even if the first two simulated EOFs represent only 58% of the variance as compared to 67% explained by the first two observed EOFs. On the other hand, EOFs are subject to significant sampling variability so that the differences between the observed patterns and the simulated patterns are likely within the sampling uncertainty.

The relationship between North Atlantic SLP and winter Iberian precipitation is the key point in trying to assess changes in regional rainfall indirectly using the large-scale results from the GCM experiments. It is, thus, of interest to determine if the model reproduces this large-scale/regional-scale relationship. We have, therefore, conducted the same CCA of SLP and Iberian rainfall as ZKS, except that we used GCM data. Again, one dominant pair of pattern is identified (Fig. 8), with a canonical correlation of 0.35, which is not significantly different from zero. The rainfall patterns represent 48% of the interannual variance and 20% of the SLP variability. The observed (Fig. 3) and simulated (Fig. 8) canonical correlation patterns are dissimilar: the simulated SLP pattern exhibits an east–west dipole structure that is clearly different from the pattern

FIG. 7. First two EOFs of the winter (DJF) SLP field in the North Atlantic area: (a) from real data (COADS, explained variances are 38% and 29%); and (b) from the GCM control run (explained variances are 31% and 27%), units are mb.

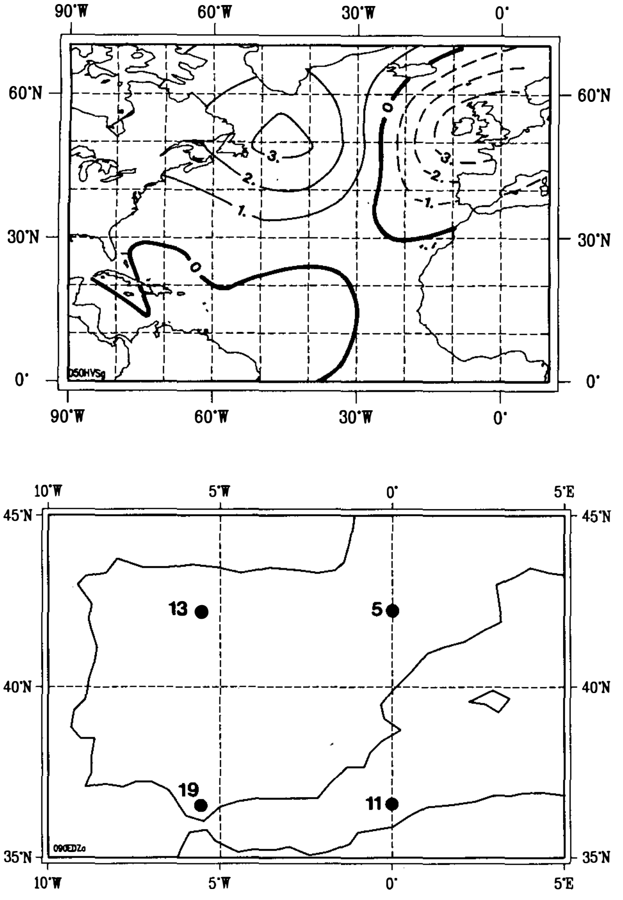


FIG. 8. Canonical correlation patterns of winter (DJF) Iberian rainfall (mm/month) and SLP (mb) in the North Atlantic derived from the GCM control run. Correlation between time coefficient is 0.35. The explained variances are 48% and 20%, respectively.

structure of the observed pattern. The rainfall pattern is characterized by a southwest to northeast gradient with the largest value in the southwest, whereas the observed pattern (Fig. 3b) exhibits a zonal gradient with largest values in the northwest.

The canonical correlation of 0.35 in the GCM is much smaller than the observed canonical correlation of 0.65. Also, the percentage of rainfall variance and of SLP variance explained by the canonical pattern is considerably smaller in the model (rainfall: 48%, SLP: 20%) than in the observations (65% and 40%). The comparison of GCM variance explained at 4 grid points with observed variance at 29 stations is an unfair procedure: the GCM field has less (statistically independent) degrees of freedom than the observed field. If ZKS had considered rainfall at only 4 stations, the CCA would certainly have resulted in a higher percentage of explained variance.

We conclude that the statistical relationship between large-scale Atlantic SLP anomalies and regional-scale Iberian rainfall is not well reproduced by the model. Since the SLP variability is reasonably well simulated by the GCM—at least its leading EOFs—these deficiencies in the simulated climate are likely due to an imperfect representation of rainfall in the Iberian peninsula. This is precisely the kind of difficulty that can be bypassed by the mixed empirical/dynamic approach suggested in this paper.

b. *The "2 CO_2" experiment*

The "2 CO_2" run was also integrated over 100 years but with a constant (roughly doubled) CO_2 concentration. The last 80 years have been used for the following analysis. In this interval the model has, at least to first-order approximation, obtained a new equilibrium during this period.

The characteristics of the *global-scale* changes simulated in the "2 CO_2" experiment are documented in Cubasch et al. (1992). We will, therefore, give only a brief summary of the global features of the induced climate change. The *warming* is generally concentrated at high latitudes, in particular over the continents in the Northern Hemisphere in winter. In some regions off the Antarctic coast a cooling is apparent. In the tropical regions only small temperature changes occur. The *rainfall* change is very noisy, and no coherent pattern of change can be identified. Increased SLP is generally found in high-latitude regions, in particular Greenland. SLP in the midlatitude Atlantic area in the "2 CO_2" climate is lower than in the control run. The atmosphere loaded with doubled CO_2 more often has a weaker zonal circulation than in the control run. Changes in the radiative balance favor a slight weakening of the atmospheric circulation in the Atlantic area.

The four grid-point-averaged annual cycles of rainfall, sea level pressure, and 2-m temperature in the "2 CO_2" atmosphere are shown in Figs. 2 and 6. We see that rainfall is reduced by about 3 mm/month throughout the year, temperature is increased by 2–3 K, and sea level pressure is almost unchanged. The differences between the "control" and the "2 CO_2" climates are much smaller than the difference between the "control" and the observed climates. This fact raises doubts about the reliability of the regional results obtained in the "2 CO_2" experiment. The simulated SLP differences between "control" and "2 CO_2" climates in the North Atlantic area, on the other hand, are smaller than the observed differences between the decades 1904–13 and 1951–60 (Fig. 4a). It is, therefore, reasonable to conclude that the CO_2-induced climate change is small enough to apply the statistical model, derived from observations, with confidence.

Using the statistical procedure outlined in section 2, we estimated the rainfall change in DJF on the Iberian Peninsula from the simulated change in North Atlantic SLP change (Fig. 9a). The signal, as derived by the GCM gridpoint rainfall data, is shown in Fig. 9b. The latter indicate a *decrease* of winter precipitation of about −10 mm/month on the average, with maximum

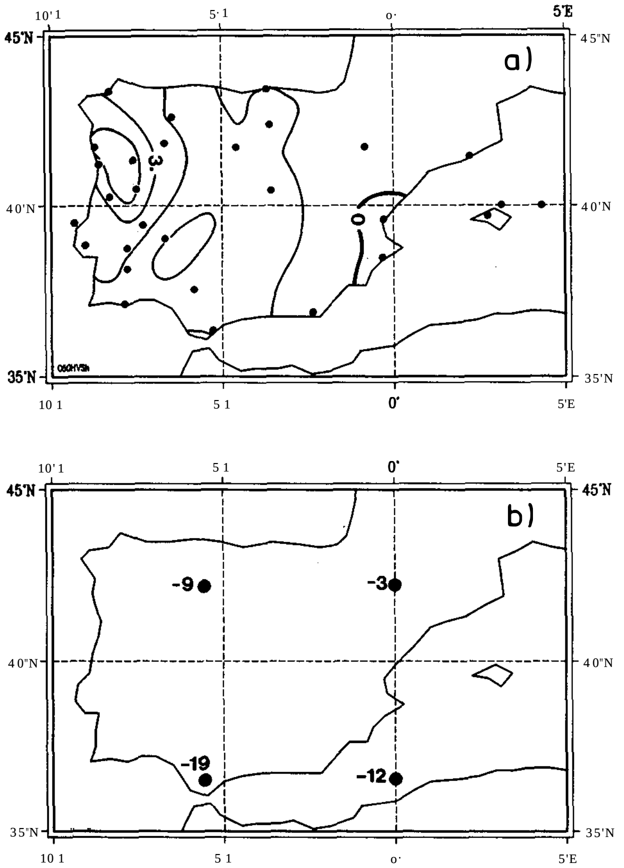


FIG. 9. Regional change of winter Iberian rainfall (mm/month) in the "2 CO_2" experiment. (a) Indirectly derived from the simulated change of North Atlantic SLP field; and (b) directly simulated by the GCM.

values in the southwest (−19 mm/month) and minimum values in the northeast (−3 mm/month). The statistical model, on the other hand, yields a very small precipitation *increase* (1 mm/month on average), with maximum values of 4 mm/month on the western side of the peninsula. That the signs and magnitude of the directly simulated and estimated rainfall changes are different suggests that in the GCM the mechanisms leading to Iberian rainfall are different from those operating in reality. This again points to the lack of skill of the GCM at regional scales.

c. *Scenario A*

In the "Scenario A" experiment (Cubasch et al. 1992), 100 years were simulated with the same initial greenhouse-gas concentration as in the control run but were growing in time according to the emission projection of the IPCC, which is nearly an exponential growth of about 1.3% per year.

The statistical model relating observed SLP anomalies to Iberian rainfall anomalies was applied to the difference of SLP fields simulated in the Scenario A run and the long-term mean of the control run. The resulting anomaly curve, smoothed with a 5-year-running mean filter, is shown in Fig. 10, together with the four gridpoint-averaged GCM anomalous precipitation.

The two curves vary coherently on the interdecadal time scale: there is a distinct time scale of about 10–20 years, with a range of about 10 mm/month. However, the amplitude of these oscillations is quite different. The high-frequency variations are not in agreement and the correlation between both curves is only 0.40. Moreover, whereas the gridpoint values always indicate a reduction of rainfall with respect to the initial conditions, there are several periods in which the estimated rainfall anomalies are positive. The downward linear trend that is observed in the averaged gridpoint rainfall [−9 mm/month per 100 year] as well as in the estimated rainfall [−7 mm/month per 100 year] is more in agreement.

In summary, as in the case of the "2 CO_2" experiment, the estimated rainfall change is different from the GCM gridpoint numbers.

4. Conclusions

A number of conclusions may be drawn from this study, with respect to methodology and to the physical problem of Iberian rainfall—its possible man-made modifications and its natural variability.

a. *Methodical aspects*

The statistical approach suggested in this paper is successful in scaling down large-scale information that is (potentially) reliably simulated in climate-change GCM experiments to regional scales relevant for users (such as hydrologists). In the terminology of forecasters, our method is a "perfect prog" approach, which means that a statistical model is developed between

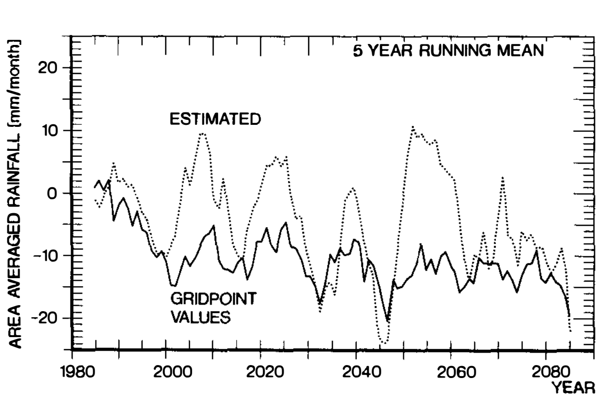


FIG. 10. Five-year-running mean time series of winter mean rainfall anomalies (mm/month) in the Scenario A experiment. Dashed: area-averaged rainfall anomalies estimated from SLP anomalies relative to the long-term mean in the control experiment; and solid: Iberian area-averaged (four grid points, see Fig. 9b) rainfall anomalies relative to the control experiment.

dynamic and prognostic quantities in the observed atmosphere, and it is applied to the simulated atmosphere unchanged.

Our approach is formally very similar to Karl et al. (1990) and Wigley et al. (1990). The main difference of our approach refers to the spatial scale of the variable used to specify the local parameter. Karl et al. (1990) used local free-atmosphere parameters, whereas Wigley et al. (1990) used area averages. Thus, in both approaches a relationship between local and regional-scale climate is established. Following the concept of Wigley et al. (1990) a good estimator for the Iberian local rainfall anomalies would be the anomalous spatially averaged precipitation. This approach would have failed in this case, since the area-average precipitation simulated by the GCM is not consistent with the simulated changes in the Atlantic SLP field, which is the real factor controlling winter Iberian precipitation. We overcome this difficulty by choosing a parameter representing the large-scale flow variability, anticipating that it would be this large scale where GCMs yield reliable results.

In principle, there are two alternative strategies that could be used, namely, analog techniques, with analogs from the paleoclimatic records (e.g., Pittock 1991), or regional models nested into GCMs. The skill of the former is often limited because of insufficient spatial or temporal resolution of the data. The other approach, with regional GCMs forced by global-scale flow, is promising (Giorgi 1990); unfortunately present day limited-area models are in almost all cases designed to be used in short case studies and not in extended-range climate studies. On the long term, the methodical difficulties of the regional models when run in the "climate mode" will be overcome. But even then, the statistical approach will still be needed as the regional–global-scale problem outlined in the Introduction will reappear, with the regional scale being the scale insufficiently modeled by the limited-area models. A similar problem is also present in weather prediction models with a finer resolution than climate models, for which the perfect prog methods were developed.

Our statistical strategy offers several advantages and limitations when compared to the nested limited-area model approach. One advantage is its technical simplicity. A second advantage is the degree of consistency with observations, often lacking in the GCMs themselves, that is enforced. The last advantage is that this approach is not limited to physical regional parameters, such as rainfall or temperature, but may also be applied to economic (e.g., agricultural yield) or ecological parameters (e.g., the width of tree rings). One limitation of the statistical approach is that it can be applied only if a strong relationship between a large-scale parameter and regional climate has been identified; often this will not be the case. Furthermore, as many statistical tools, it is not necessarily valid beyond the range of the data used to fit the model, where the relationships between the anomalies are supposed to be linear.

b. Physical aspects

This study draws an important conclusion for the users of the results of GCM experiments: The reliability of GCM results depends on the spatial scale. For multigrid spatial scales larger than N point distances, with $N \geq 8 - 4$, the GCMs are (potentially) reliable, whereas all results on the regional scale are questionable. The main idea in this paper is to translate the information generated by the GCMs at skillful scales to regional scales.

The change of Iberian rainfall directly simulated by the GCM at its four grid points is not consistent with the rainfall change derived from the North Atlantic SLP change both in the equilibrium 2 CO_2 experiment and in the transient IPCC Scenario A experiment. Also, the patterns deviate: the directly simulated numbers indicate a maximum of the signal, 19 mm/month, in the equilibrium experiment at the grid point in the southwest of the peninsula, whereas the empirical method places the strongest response in the mountainous northwestern part of Spain and Portugal. Clearly, the low horizontal resolution of the T21 model is not able to represent topographic subtilties like the Iberian Peninsula, because step function–like features (coastal mountain regions) are smoothed out and flattened by the spectral representation.

It should not be forgotten that the results presented here concerning the future changes of Iberian rainfall strongly depend on the ability of the GCM to simulate large-scale changes of the atmospheric flow, and this ability is much more difficult to estimate. It may well happen that different GCMs produce different results. In fact, the very same climate model used in this paper predicts changes in the DJF SLP field over the North Atlantic of different signs when run in an equilibrium 2 CO_2 mode or in a transient mode. Fully coupled atmosphere–ocean climate models are relatively new in climate research, so that future models with better resolution, parameterization, and coupling schemes may well produce other results. This question is just an aspect of our uncertainty with the present climate models.

Both Iberian station rainfall data and the rainfall changes derived indirectly from North Atlantic SLP indicate that there has been an almost continuous increase of Iberian winter rainfall since the beginning of this century of more than 10 mm/month, or 20%–25% of its 1900–10 level. This increasing trend is overlaid with significant variations that have a range of about 8 mm/month and a time scale of about 20 years. It should be remarked that the parameters entering the statistical model were fitted using data in a relatively short period of time (1951–80) but that the model is still capable of reproducing these long-term features. This fact supports our initial assumption that this method might be applied to variations of North Atlantic SLP variations, regardless if they reflect interannual variability or long-term climate drifts.

This increasing rainfall observed from the beginning of this century and the prospects envisaged by the Scenario A experiment are not consistent because the GCM transient experiment predicts a long-term decrease of Iberian rainfall in the next hundred years. The same can be said about the SLP field over the North Atlantic (compare Figs. 5 and 10). From this fact one may reach different conclusions: either the observed trend is not caused by the increasing greenhouse-gas concentration in the atmosphere, or the model is not properly simulating the future changes in the atmospheric flow. If the first possibility is correct, then other natural mechanisms not incorporated in the GCM should be counteracting the effects of the greenhouse-gas forcing, indicating that reliable climate-change estimate at regional scales will require great care.

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REFERENCES

Barnett, T., and R. Preisendorfer, 1987: Origins and levels of monthly and seasonal forecasts skill for United States surface air temperatures determined by canonical correlation analysis. *Mon. Wea. Rev.*, **115**, 1825–1850.

Cohen, S. J., and T. R. Allsopp, 1988: The potential impacts of a scenario of CO_2-induced climatic change on Ontario, Canada. *J. Climate,* **1,** 669–681.

Cubasch, U., K. Hasselmann, H. Hoeck, E. Maier-Reimer, U. Mikolajewicz, B. D. Santer, and R. Sausen, 1992: Transient greenhouse warming computations with a coupled ocean–atmosphere model. *Climate Dyn.*, **8**, 55–69.

Giorgi, F., 1990: Simulation of regional climate using a limited-area model nested in a general circulation model. *J. Climate,* **3,** 941–963.

Grotch, S. L., and M. C. MacCracken, 1991: The use of general circulation models to predict regional climatic change. *J. Climate,* **4,** 286–303.

Hense, A., R. Glowienka-Hense, H. von Storch, and U. Stähler, 1990: Northern Hemisphere atmospheric response to changes of Atlantic Ocean SST on decadal time scales: A GCM experiment. *Climate Dyn.*, **4**, 157–174.

Houghton, J. T., G. J. Jenkins, and J. J. Ephraums, Eds., 1990: Climate change. The IPCC Scientific Assessment. Cambridge University Press, 364 pp.

Ikeda, M., 1989: Decadal oscillations of the air–sea ocean system in the Northern Hemisphere. *Atmos.-Ocean,* **28,** 106–139.

Karl, T. R., W.-C. Wang, M. E. Schlesinger, R. W. Knight, and D. Portman, 1990: A method of relating general circulation model simulated climate to the observed local climate. Part I: Seasonal statistics. *J. Climate,* **3,** 1053–1079.

Lamb, P., and R. Peppler, 1987: The North Atlantic oscillation: Concept and an application. *Bull. Amer. Meteor. Soc.*, **68,** 12 218–12 225.

Mikolajewicz, U., and E. Maier-Reimer, 1990: Internal secular variability in an ocean general circulation model. *Climate Dyn.*, **4,** 145–156.

Pittock, B., 1991: Developing regional climate change scenarios: An Australian approach. *Proc. Intl. Conf. on Climate Impacts on the Environment and Society,* Tsukuba.

Roeckner, E., L. Dümenil, E. Kirk, F. Lunkeit, M. Ponater, B. Rockel, R. Sausen, and U. Schlese, 1989: The Hamburg version of the ECMWF model (ECHAM). GARP Report No. 13, WMO, Geneva, WMO/TP No. 332.

Shea, D., 1986: Climatological Atlas: 1950–1979. Surface air temperature, precipitation, sea-level pressure and sea surface temperature. NCAR Tech. Note, 35 pp.

Smith, J., 1991: The Potential impacts of climate change on the Great Lakes. *Bull. Amer. Meteor. Soc.*, **72,** 21–28.

Wigley, T. M. L., P. D. Jones, K. R. Briffa, and G. Smith, 1990: Obtaining subgrid scale information from coarse-resolution general circulation model output. *J. Geophys. Res.*, **95,** 1943–1953.

Zorita, E., V. Kharin, and H. von Storch, 1992: The atmospheric circulation and sea surface temperature in the North Atlantic area in winter: Their interaction and relevance for Iberian precipitation. *J Climate,* **5,** 1097–1108.