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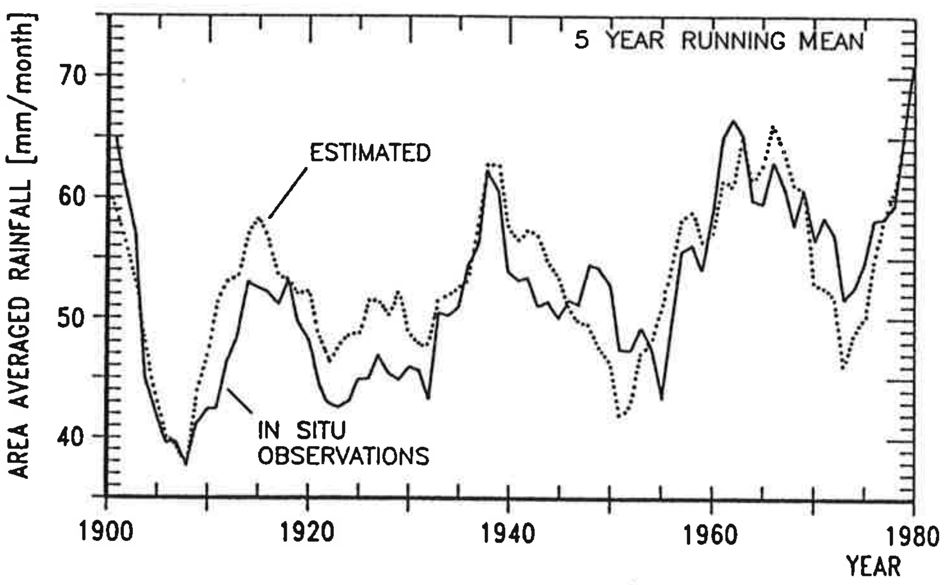

DOWNSCALING OF GLOBAL CLIMATE CHANGE ESTIMATES TO REGIONAL SCALES: AN APPLICATION TO IBERIAN RAINFALL IN WINTERTIME.

by

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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 deduce regional scale features from Climate General Circulation Model (GCM) simulations has been designed and tested. The main idea is to identify the characteristic patterns of observed simultaneous variations of *regional* climate parameters and of *global scale* atmospheric flow.

Using the Canonical Correlation technique the global-scale parameter "North Atlantic sea-level pressure" is related to the regional parameter "winter (DJF) mean Iberian Peninsula rainfall". The skill of the resulting statistical model is shown by reproducing, to good approximation, the winter mean Iberian rainfall from 1900 to 1980 from the observed North Atlantic mean SLP distributions.

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 "$2\times CO_2$" doubling-experiment the simulated change of the mean North Atlantic SLP field suggests insignificantly increased area-averaged rainfall of 1 mm/month, with maximum values of 4 mm/month in the northwest of the Peninsula. In contrast, the directly simulated change of precipitation, at the four GCM grid points representing the Iberian Peninsula, 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 differ from the directly simulated rainfall changes: over the experimental range of 100 years, the area averaged rainfall decreases by 7 mm/month (statistical model) and by 9 mm/month (grid-point values).
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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 adopted: The *minimum scale* is defined as the distance between two neighboring grid points of the GCM, whereas the *skillful scale* is larger than $\mathcal{N}$ grid point distances. It is likely that $\mathcal{N} \geq 8$ but certainly $\mathcal{N} \geq 4$. Scales larger than the skillful scale are denoted as *global 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 ≤ 2000 - 4000 km.

It is widely accepted that present day GCMs are able to simulate the global-scale atmospheric state in a generally realistic manner, and it is believed that these models are the adequate tool to predict global-scale climate changes. Even though GCMs produce values on the minimum scale, their implications for regional climate are questionable (Grotch and MacCracken, 1991).

The idea of global-scale reliability is illustrated in Figure 1, showing the observed long-term mean rainfall distribution and that which is simulated. Global features such as the rain-bands marking the 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 mid-latitudes 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 is 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. 10a), the observed numbers are averages of 29 stations (see Fig. 3b)). Certainly, part of the discrepancy is also due to deficiencies and the irregular distribution of the observing network.

Figure 1.
Annual mean precipitation (mm/month) derived from observations (Shea, 1986) and from the control "1×CO_2"-run (ECHAM1/LSG coupled GCM).

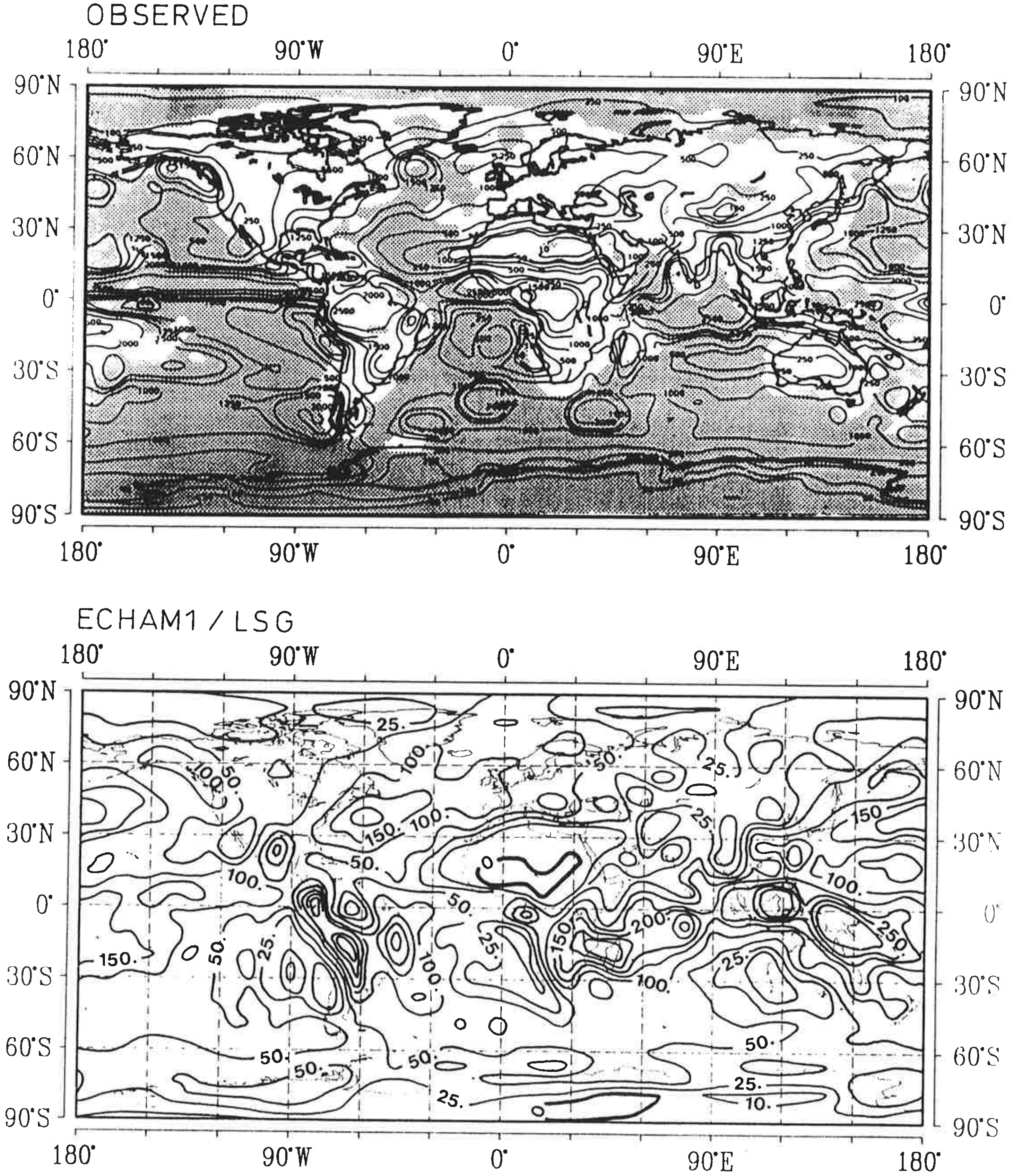
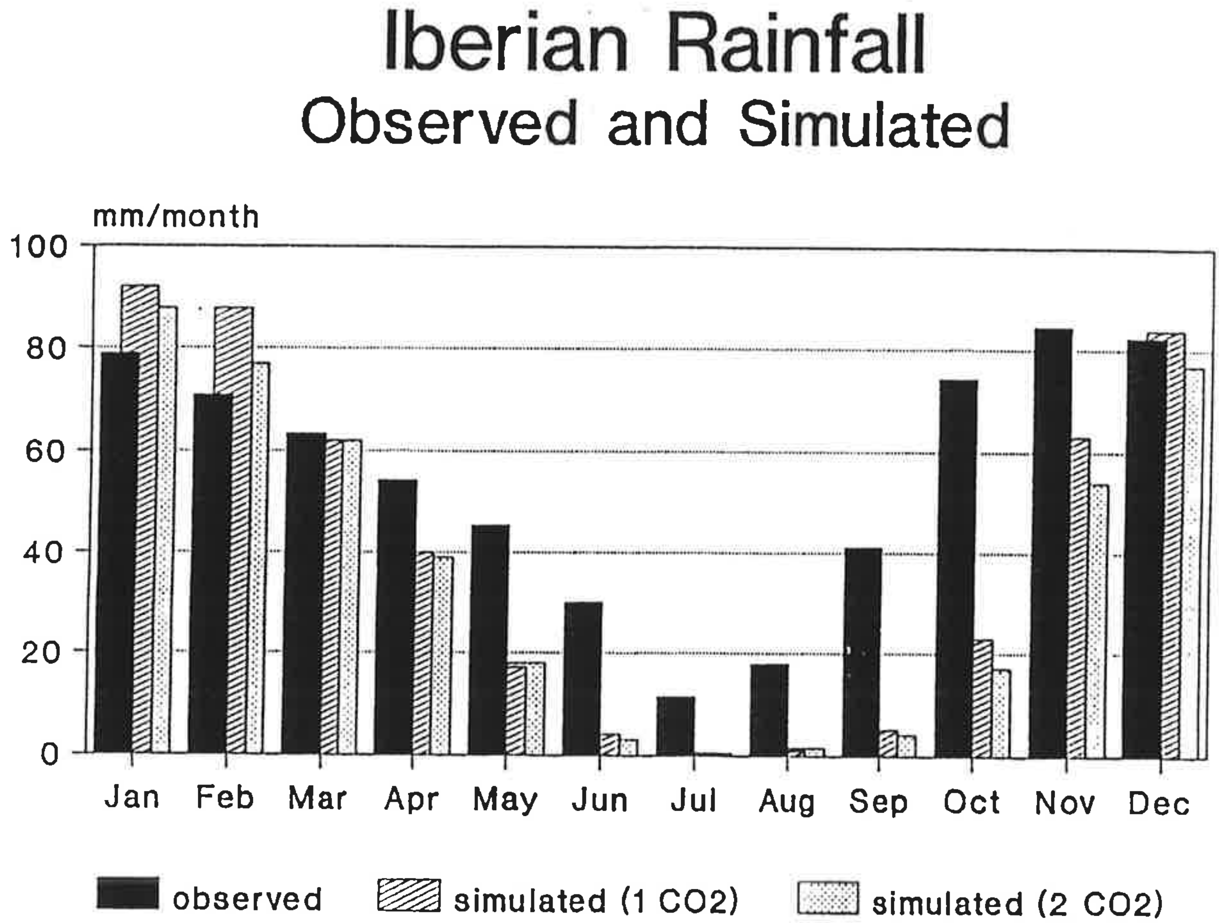


Figure 2.
Mean annual cycle of precipitation averaged over the Iberian peninsula (mm/month) derived from the in-situ observations, from the GCM control run and from the GCM "$2\times CO_2$" experiment.
The observed data are derived from 29 stations included in the WMSC data-set. The GCM data are averages of 4 grid-points roughly coincident with the Iberian Peninsula (for the mathematical locations, see Fig. 9b).



Many customers of climate change forecasts, such as hydrologists, request information on the regional scale. An additional problem is that the demanded information, e.g. local rainfall, is dependent on sub-grid-scale processes. These sub-grid-scale processes are taken into account in GCMs by means of *parameterizations*, i.e., by semi-empirical methods which 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 global 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 global-scale changes, and, whenever possible, to infer regional changes by sensibly projecting the global-scale information onto 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 global flow. This mixed empirical-dynamic approach relies on the assumption that the response of the regional climate to a changing global mean flow, due either to internal climate variability or to external forcing, is the same in both cases. This unproven assumption may be considered reasonable as long as changes in the global flow are sufficiently small.

Pursuing the latter approach in the present paper, we illustrate the approach by considering the winter (DJF) precipitation on the Iberian Peninsula. In a previous paper Zorita et al. (1991; referred to as ZKS in the following) showed with Canonical Correlation Analysis (CCA) that there is a strong statistical relationship between Iberian Peninsula 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%). It was found that the SLP pattern is closely related to the North Atlantic Oscillation, a well documented large-scale feature of the winter atmospheric circulation in the North Atlantic (e.g., van Loon and Rogers, 1978; and other references in ZKS).

Formally similar procedures have been proposed by Wigley et al.(1990) and Karl et al. (1990). However, these procedures do not operate on the *global* scale. Instead, they try to exploit the GCM regional or minimum scale information to derive sub-grid-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 that are consistent with the atmospheric flow changes simulated in two experiments conducted with the ECHAM1/LSG model. In one experiment, the concentration of CO_2 is doubled from the beginning, and in the second the concentration is continuously increased ("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 Global Scale Anomalies

In this section, we first specify the statistical model which relates the irregularly distributed Iberian Peninsula (Spain and Portugal) rainfall field to the gridded observed sea-level pressure (SLP) field in the Atlantic Sector. The analysis is limited to winter which is the season with maximum rainfall on the Iberian Peninsula (see Figure 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 analysed seasonal mean rainfall from 29 stations (from the World Meteorological Station Climatology (WMSC) data-set) and North Atlantic sea-level pressure (from COADS) from 1950-80, and found one dominant pair of patterns. The SLP pattern (Fig. 3a) is quite similar to the North Atlantic Oscillation (NAO), the dominant mode of large-scale variability in the North Atlantic sector (e.g., van Loon and Rogers, 1978; Rogers, 1984; Lamb, 1987). For the sake of convenience we identify our pattern with the NAO. The rainfall pattern (Fig. 3b), which accounts for 65% of the total interannual variance, indicates that maximum anomalies of Iberian rainfall associated with the NAO take place in the western part of the peninsula, and that anomalies in the southeast part are small.

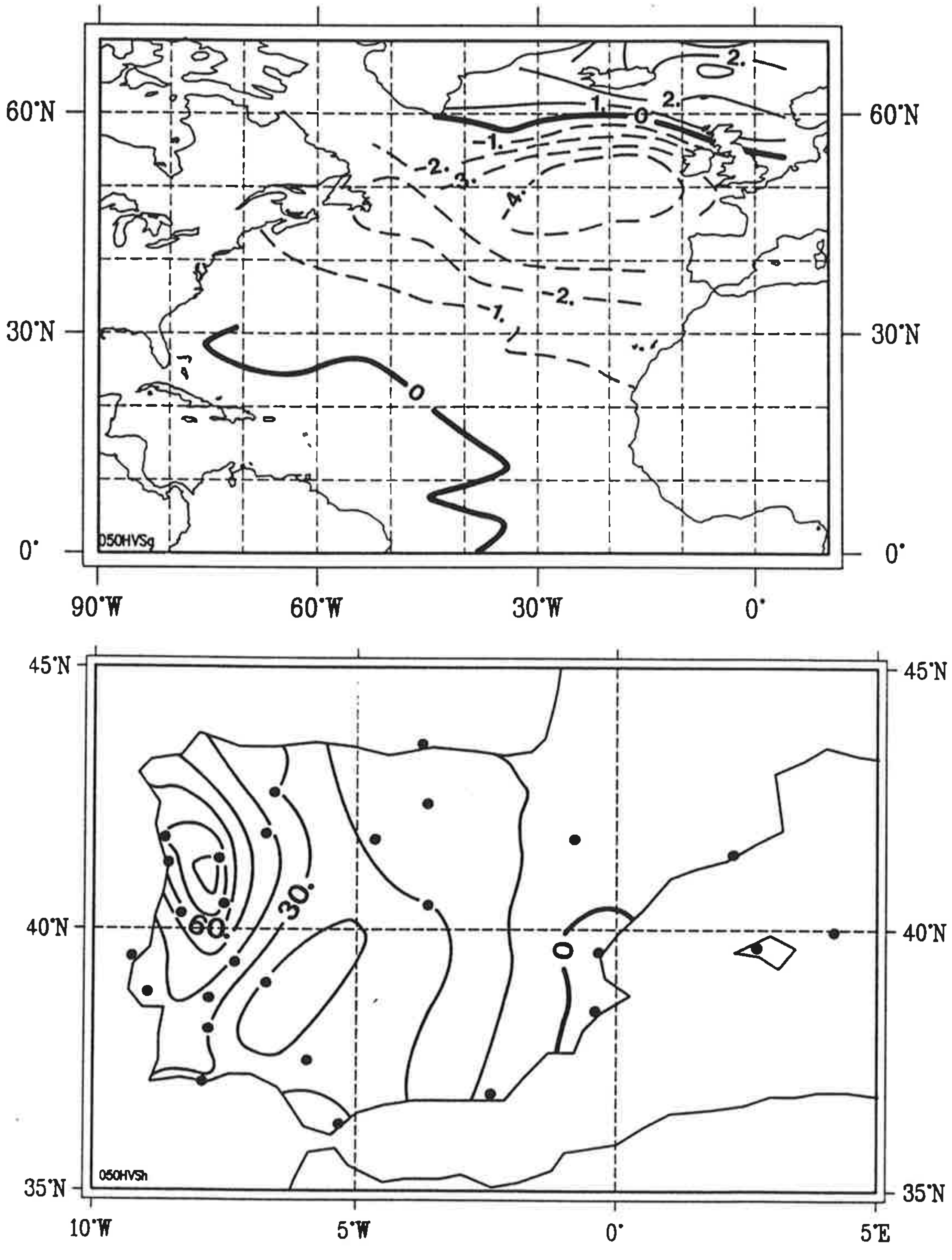
The two patterns represent a reasonable physical relationship, as follows. If the sea-level pressure pattern (Fig. 3a) has a positive coefficient then the mean advection of maritime air from the ocean to the Iberian Peninsula is intensified, the process of lifting humid air over the coastal mountains of the Peninsula is more efficient than on average and rainfall is enhanced. Conversely, if the coefficient is negative then the mean advection is weakened and, in association, less rain falls. 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

Figure 3.

Canonical correlation patterns of observed winter (DJF) Iberian rainfall and simultaneous SLP field in the North Atlantic area. The correlation between the associated time coefficients is 0.75. They explain about 65% and 40% of the respective total variances.

The SLP data are derived from COADS on a 10°×4° lat-long grid from 1950 through 1980. The rainfall data comprise 29 stations, the locations of which are marked by dots, from WMSC covering the same period.

(From Zorita et al., 1991)



controlled by the NAO. This is the rationale for using the NAO, as given by the SLP canonical correlation pattern and its coefficient, as a predictor of the Iberian rainfall anomalies.

We use ZKS's CCA to construct a simple statistical regression model to relate Iberian rainfall to North Atlantic SLP. If $\mathfrak{S}$ and $\mathfrak{R}$ are the two canonical correlation patterns for SLP and rainfall respectively then the time series s(t) and r(t) represent optimally correlated signals. The time coefficient s(t) is obtained as the dot product $s(t) = \mathbf{S}(t)\cdot\mathfrak{S}^*$ of the SLP anomaly field **S**(t), at time t, with the adjoint CCA pattern $\mathfrak{S}^*$. Similarly: $r(t) = \mathbf{R}(t)\cdot\mathfrak{R}^*$. The canonical correlation coefficient ρ_{sr} between s(t) and r(t) is $\rho_{sr} = 0.75$. If the SLP field contains the signal $s(t)\mathfrak{S}$, then the best estimate $\hat{\mathbf{R}}(t)$ for the simultaneously existing rainfall signal is obtained by the regression

$$(1) \qquad \hat{\mathbf{R}}(t) = \hat{r}(t)\mathfrak{R} = \alpha\cdot s(t)\cdot\mathfrak{R}$$

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 r(t) and s(t).

If we regard the SLP coefficient s(t) as an approximate index of the state of the NAO, the regression (1) linearly relates an anomaly of the NAO, excited either by natural low-frequency variability or by anthropogenic climate changes, to simultaneous Iberian rainfall anomalies.

To obtain the SLP-consistent rainfall anomaly at a given time t, the SLP index s(t) is obtained by projecting the SLP anomaly field S(t) onto the CCA pattern $\mathfrak{S}$, and then applying regression (1). Clearly, this procedure may be used for observed or simulated SLP anomaly fields.

Our procedure is able to describe only the proportion (65%) of seasonal rainfall variability which can be traced to changes in the NAO. A natural question is whether there are other global-scale processes which 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 impossible.

b) Reconstruction of Iberian DJF rainfall anomalies 1900-1980

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, shown in Fig 4, is statistically significant. 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 observing procedures.

The varying atmospheric circulation over the Atlantic Ocean provides an opportunity to test the reliability of our statistical procedure to specify Iberian rainfall anomalies. To accomplish this, SLP anomalies S(t) were derived for each DJF season between t = 1900 and t = 1980. The respective consistent rainfall anomalies $\hat{R}(t)$ were estimated with the regression (1). The estimates $\hat{R}$ were verified with in-situ observations from an Iberian rainfall data-set compiled by Elvira Zurita (Universidad Complutense, Madrid) for 30 Spanish stations. The WMSC data-set could not be used because it contained only two stations with a long enough record. To avoid inconsistencies we are considering only those stations which are contained in both the "Complutense" data-set and the WMSC data-set.

First we address the difference between the two decades 1904-13 and 1951-60. In Fig 4a, the North Atlantic SLP field is shown. In the early part of the 20th century, the westerly wind area was shifted northward compared to the 1951-60 decade, so that, probably, fewer baroclinic disturbances were traveling to the Iberian Peninsula than in the middle of the century. Consistently,

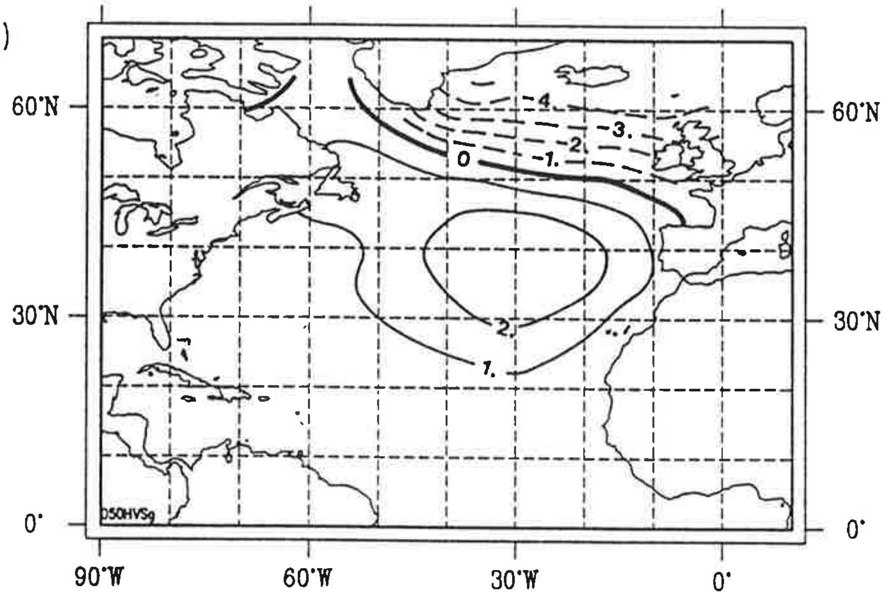
Figure 4.

Interdecadal DJF-differences between 1903-14 and 1951-60.

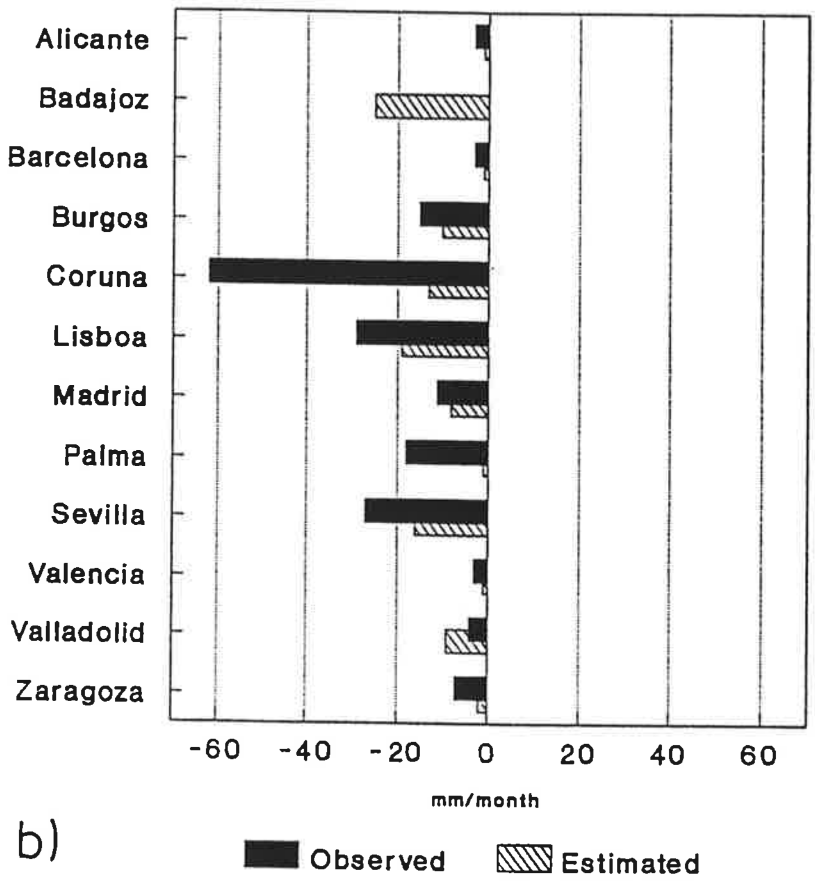
a) Observed winter mean SLP difference (mb), derived from NCAR data.

b) Winter precipitation differences (mm/month) at the 12 stations contained in both the Complutense data-set and in the WMSC data-set. Solid: in-situ observations. Hatched: rainfall difference estimated from the SLP difference shown in a).

a)



Decadal DJF rainfall differences 1904-13 vs. 1951-60



b)

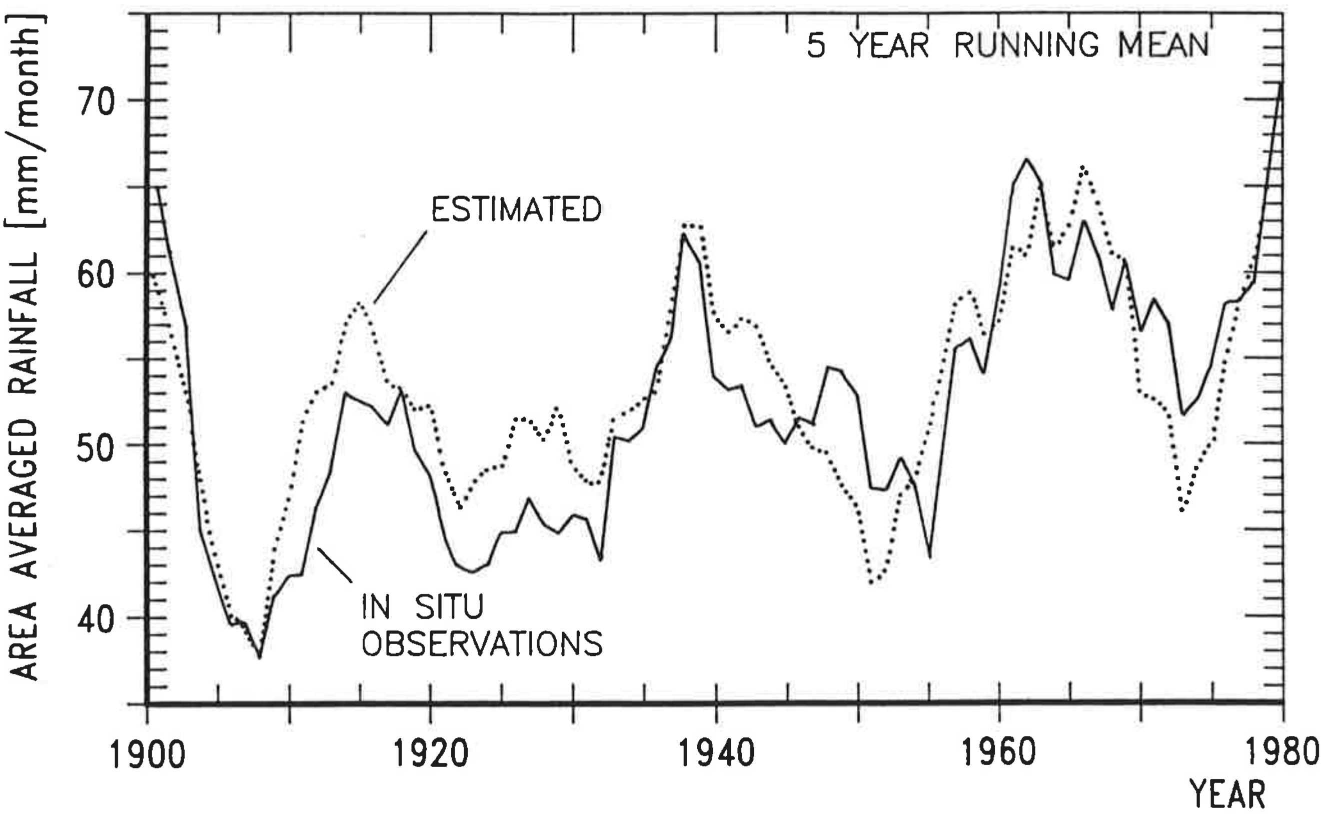
the estimated and observed DJF mean precipitation differences, $\hat{R}$(1904-13) - $\hat{R}$(1951-60) and R(1904-13) - R(1951-60), at the 12 joint Complutense/WMSC stations are all negative (Fig 4b). Apart from Badajoz, the sign of the estimated and observed anomalies coincide in all stations. At some locations, such as Madrid, Valencia and Burgos, the coincidence is very good, but at Coruna the observed change is five-times the estimated signal.

In Fig. 5 we show the temporal evolution (5-year-running mean) of the spatial averages of the estimated and 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. Interestingly both curves exhibit coherent long-term variations. Spectral analysis of the unfiltered data (not shown) reveal that these 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 NAO (Ikeda, 1989 and references therein). The mechanism responsible for the trend is, however, unknown. One might speculate that the trend is a consequence of the increasing concentration of greenhouse-gases in the atmosphere.

Figure 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 the lack of data in the WMSC data-set in the early part of the century, not the WMSC stations but those with a complete record 1900-1980 in the Universidad Complutense station data set have been used.



3. GCM EXPERIMENTS

In this study we examine two extended range experiments with a coupled atmosphere-ocean GCM which were carried out at the Max-Planck-Institut für Meteorologie in Hamburg (Cubasch et al., 1991). 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 (LSG) is a "Large-Scale-Geostrophic model" (Mikolajewicz and Maier-Reimer, 1990) with the same horizontal resolution as the atmosphere model (ca. 5.6^{o}) 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 doubling of the present day greenhouse-gas level. In the second experiment "Scenario A" a continuously increasing greenhouse-gas concentration is specified according to the IPCC Scenario A ("business as usual"). Both experiments have been run for a period of 100 years and will be compared against a 100-year "control" integration, i.e. an experiment run with the present day greenhouse-gas concentration.

In this Section we describe the model's ability to simulate the observed climate by examining the control run on regional and global scales. Then the climate change experiments are analysed with respect to the Iberian rainfall.

a) Control run

The following description is based on the long-term means built upon the last 80 y which 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.

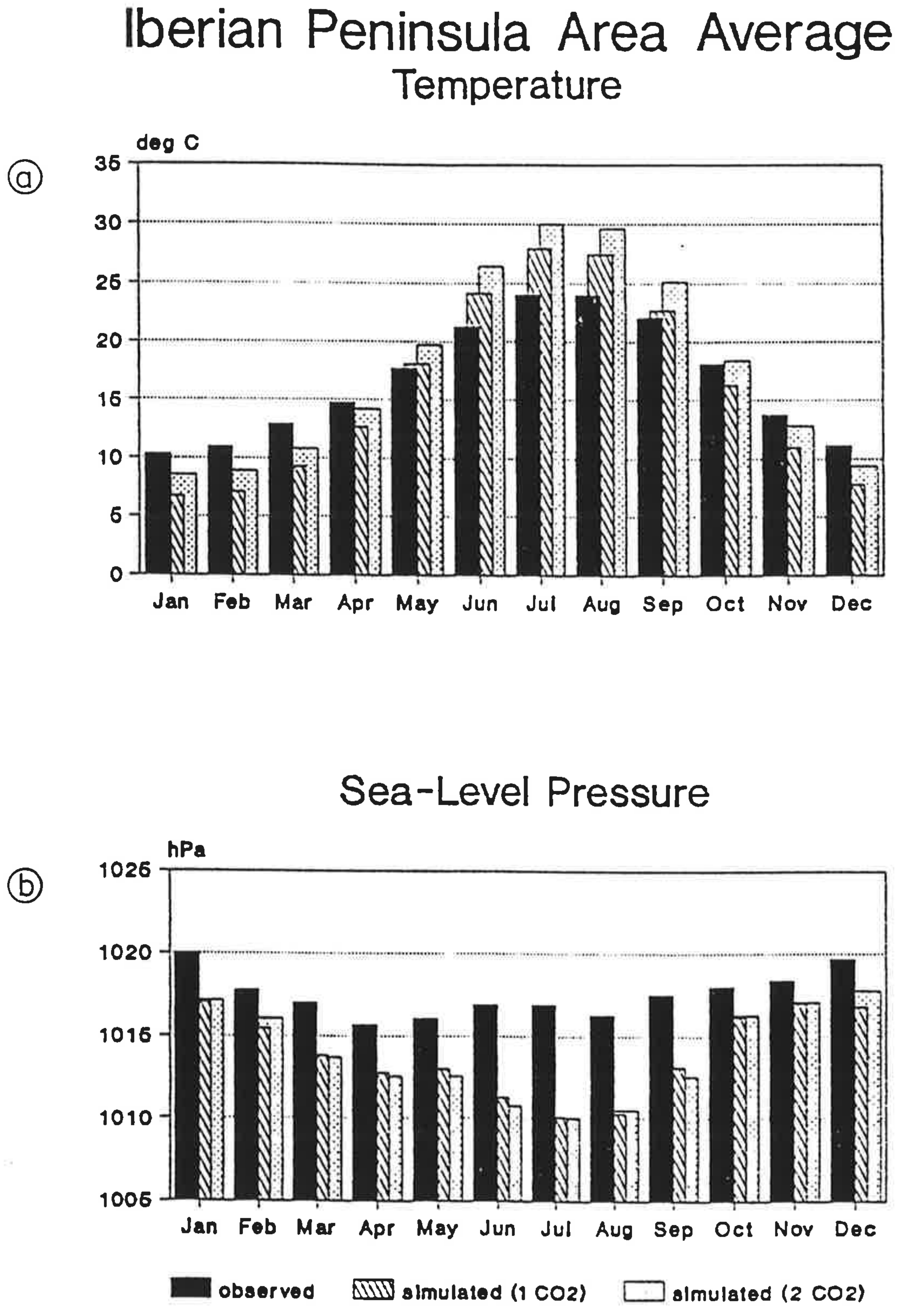
In Figs. 2 and 6 we show the time evolution of the area-averaged Iberian rainfall, sea-level pressure and 2m-temperature. The GCM figures represent the mean of the four grid-points that might be connected with the Iberian Peninsu-

Figure 6.

Annual cycles of the area-averaged long-term means of Iberian Peninsula surface air temperature and sea-level pressure. The observed values are derived from the 29 WMSC stations irregularly distributed on the peninsula; the values simulated in the control run and in the "2×CO_2" run represent the mean over the four grid-points shown in Figure 9a.

(a) interannual means of surface-air temperature (K)

(b) interannual means of sea-level pressure (hPa)



la (for the mathematical locations see Fig. 9a). The "observed" curves have been derived from the 1950-80 reports of the 29 WMSC stations.

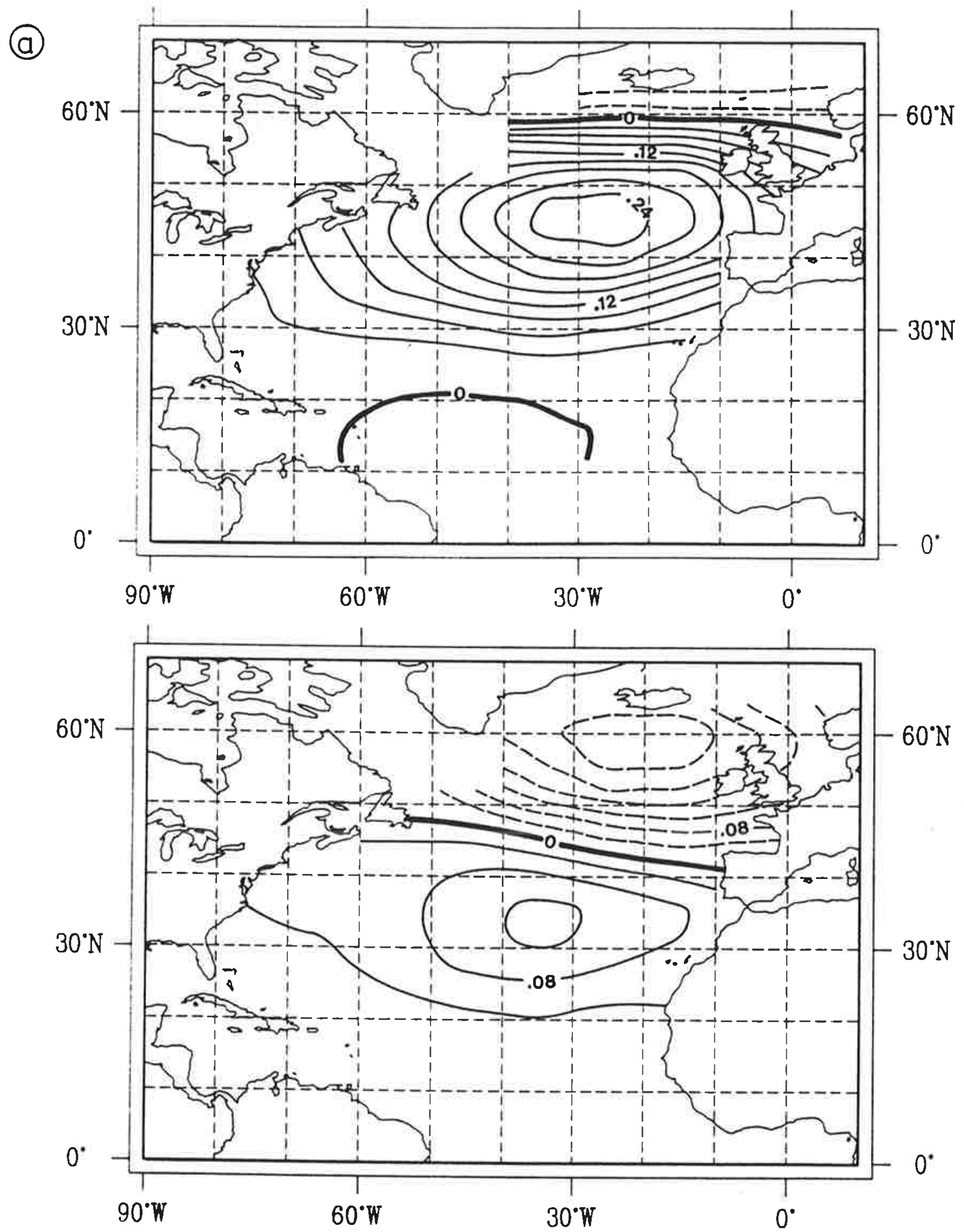
The forms of the annual marches of rainfall, sea-level pressure and 2m-temperature in the simulated data roughly agree with observations. There are, however, severe deviations with respect to details. The modeled SLP is too low throughout the year. Temperature is underestimated in winter and overestimated 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 EOFs of the observed and simulated DJF SLP in the North Atlantic. They are all of large scale, and the first observed pattern (38%), which has been identified by Barnston and Livezey (1987) as representing the NAO, is similar to the first simulated (33%); and the second observed (29%) resembles also the second simulated (24%). We conclude that our basic assumption, namely that the GCM is doing a credible job on the global scale, is justified, even if the first two simulated EOFs represent only 57% 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 probably within the sampling uncertainty.

The relationship between the NAO and winter Iberian precipitation is the key-point in trying to assess changes in regional rainfall indirectly using the global-scale results from the GCM experiments. It is thus of interest to determine if the model reproduces this global/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 patterns is identified (Fig. 8), with a canonical correlation of 0.38 which is not significantly different from zero. The rainfall patterns represents 48% of the interannual variance and 20% of the SLP variability. The observed and simulated patterns are dissimilar: the simulated SLP pattern exhibits an east-west dipole structure clearly different from the pattern structure of the observed pattern. The

Figure 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%),
(b) from the GCM control run (explained variances are 33% and 24%).
Units are hPa



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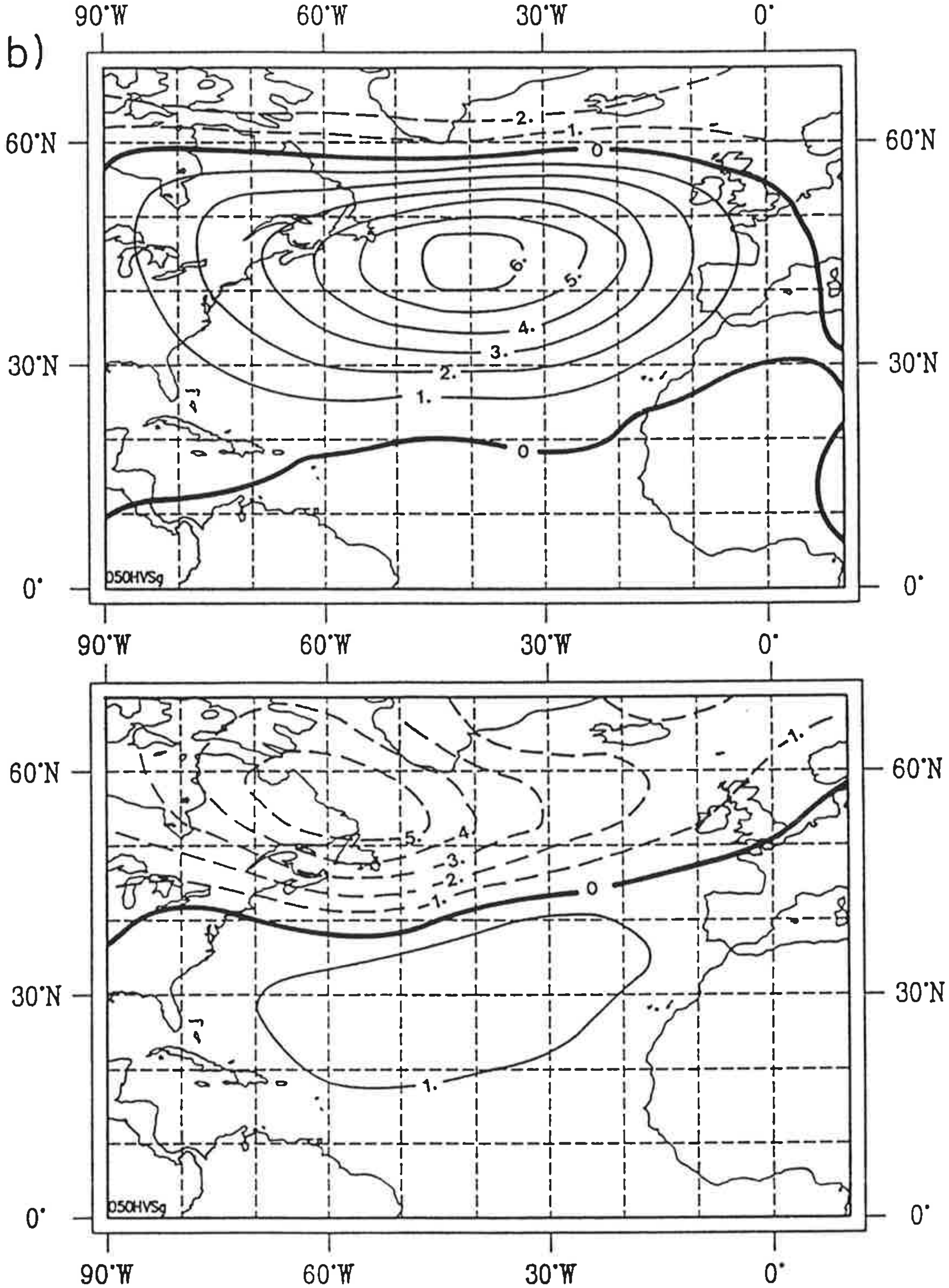
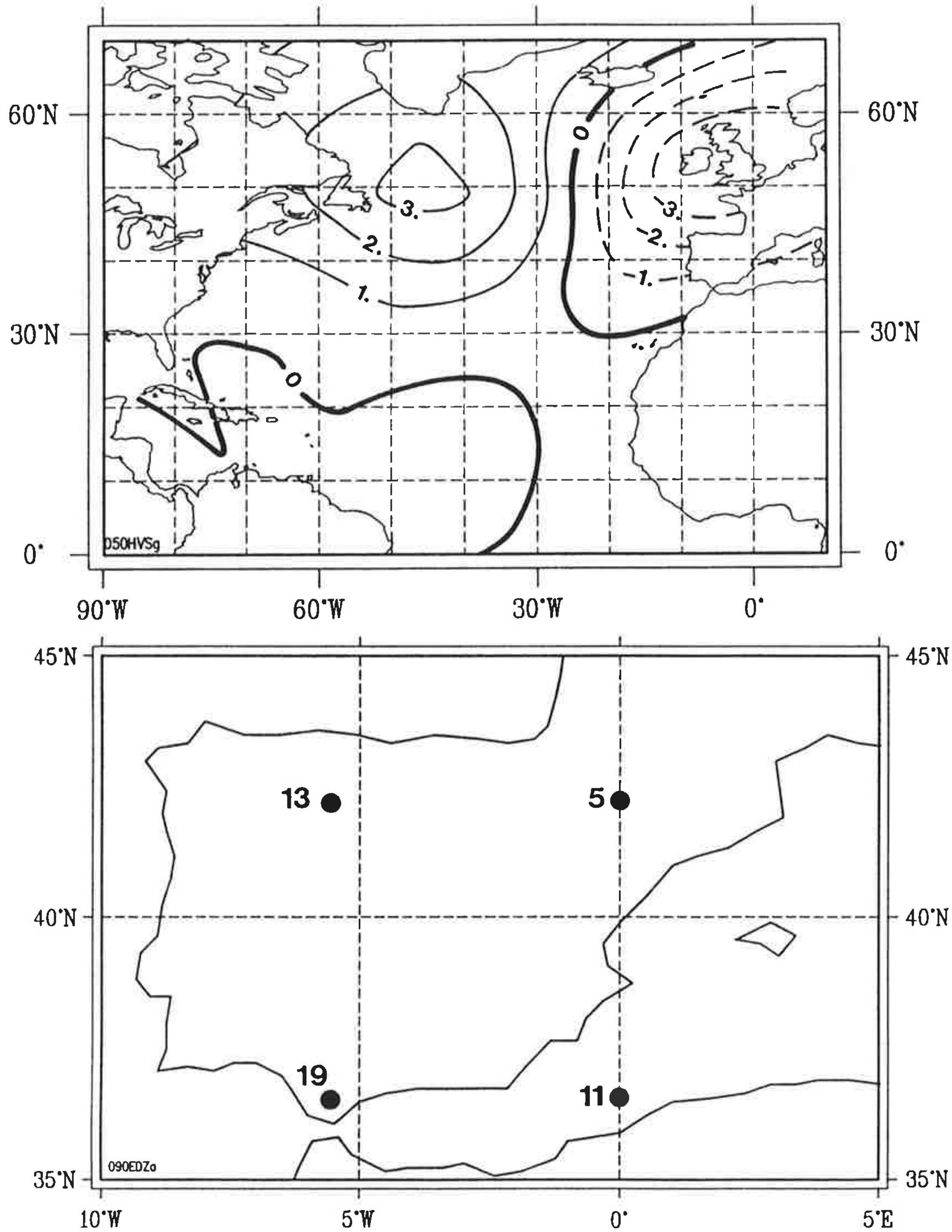


Figure 8.

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 coefficients is 0.38. The explained variances are 48% and 23%, respectively.



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 0.38 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.

From the above we conclude that the statistical relationship between global-scale North Atlantic SLP anomalies and regional-scale Iberian rainfall is not well reproduced by the model. Since the global-scale NAO pattern is fairly well simulated by the GCM, as the first EOF of the SLP field, these deficiencies in the simulated climate are probably due to an imperfect representation of rainfall in the Iberian peninsula. This is precisely the kind of difficulty that can be by-passed by the mixed empirical/dynamic approach suggested in this paper.

b) The "$2\times CO_2$"-experiment

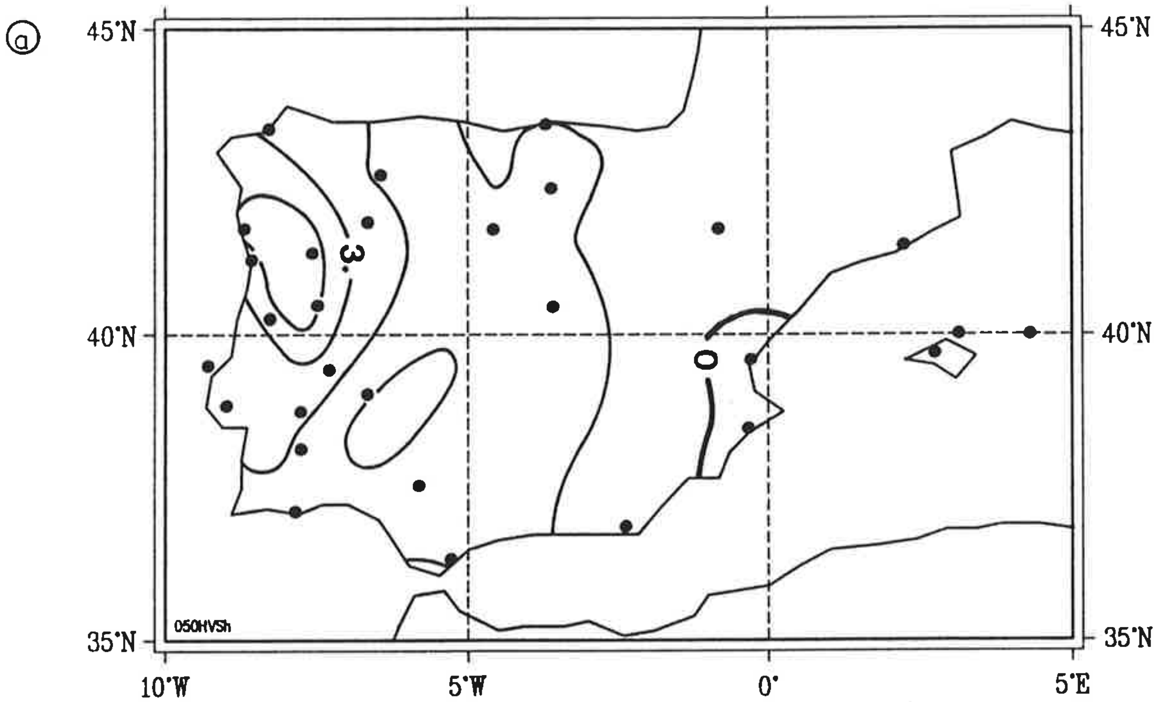
The "$2\times CO_2$" run was also integrated over 100 years but with a constant (doubled) CO_2 concentration. The last 80 years have been used for the following analysis. In this interval the model has, at least to first order approximation, obtained a new equilibrium during this period.

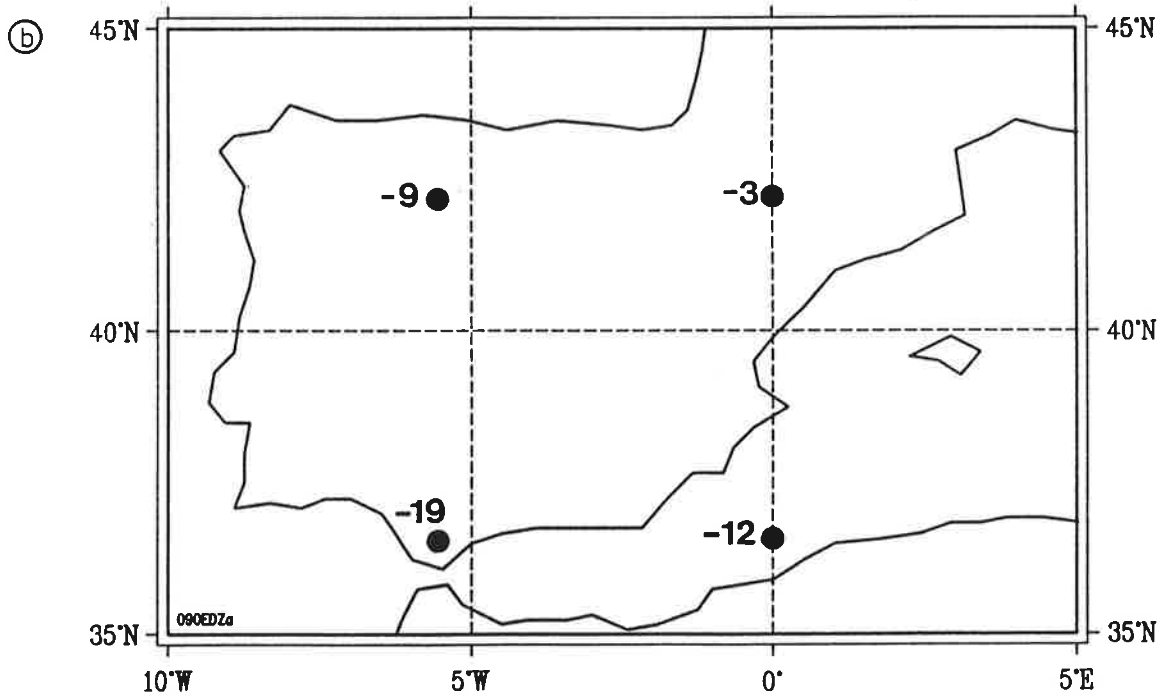
The characteristics of the *global-scale* changes simulated in the "$2\times CO_2$" experiment are documented in Cubasch et al. (1991). We will therefore give only a brief summary of the global features of the induced climate change. The *warming* is generally concentrated at high latitudes, in particular 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 temperatures 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 mid-latitude 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 "low NAO index" than in the control run. Changes in the radiative balance favor a slight weakening of the atmospheric circulation in the Atlantic area.

The 4-grid-point averaged annual cycles of rainfall, sea-level pressure and 2m-temperature in the "2×CO_2"-atmosphere are shown in Figs. 2 and 6. We see that rainfall is reduced by about 10 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, however, much less 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 (Fig. 9a). The signal as derived by the GCM grid-point rainfall data is shown in Fig. 9b. The latter indicates a *decrease* of winter precipitation of about -11 mm/month on the average with maximum values in the southwest (-19 mm/month) and minimum values in the northeast (- 3 mm/month). The statistical model, 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.

Figure 9.
Regional change of winter Iberian rainfall (mm/month) in the "2×CO_2"-experiment.
(a) Directly simulated by the GCM.
(b) Indirectly derived from the simulated change of the North Atlantic SLP field.





c) Scenario A

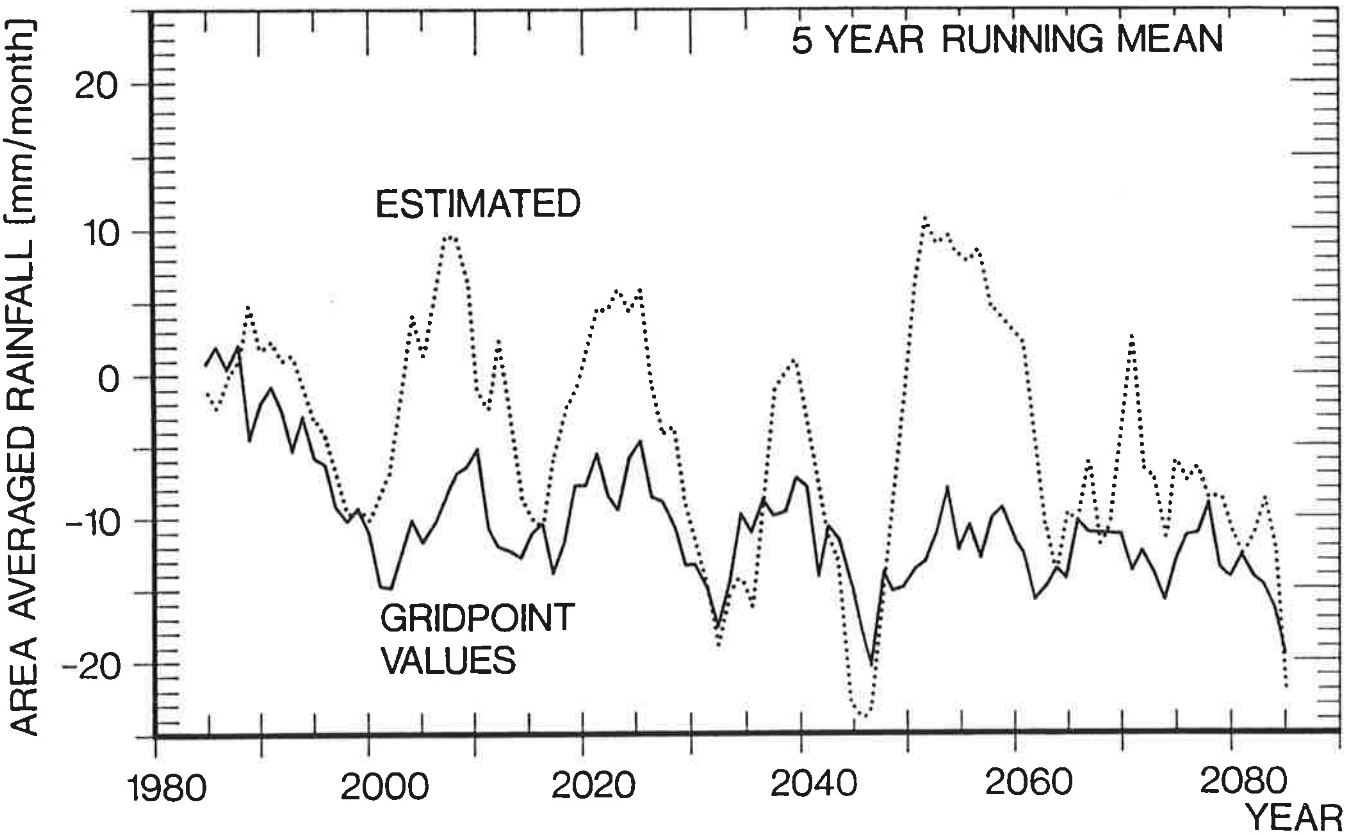
In the "Scenario A"-experiment 100 years were simulated with an initial greenhouse-gas concentration corresponding to that observed in 1985 and growing according to the emission projection of the IPCC, which is nearly an exponential growth of about 1.3% per year.

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 4 grid-point averaged anomalous GCM 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 high-frequency variations are not in agreement: the correlation coefficient is only 0.40. This again points to a deficient representation of Iberian precipitation in the model. The downward linear trend that is observed in the averaged grid-point rainfall (-9 (mm/month)/(100 years)) as well as in the estimated rainfall (-7 (mm/month)/(100 years)) is more in agreement.

We conclude that the rainfall change that is indirectly derived from the large-scale SLP change is considerably different from the grid-point rainfall change.

Figure 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.
Solid: Iberian area average (4 grid-points, see Fig. 9a) rainfall anomalies relative to the control experiment.



4. CONCLUSIONS

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

a) Methodological Aspects

The statistical approach suggested in this paper has turned out to be successful in downscaling large-scale information which 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; that is, a statistical model is developed between dynamic and prognostic quantities in the observed atmosphere and it is applied to the simulated atmosphere unchanged.

Our approach is formally 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. used local free-atmosphere parameters, whereas Wigley et al. used area averages. Thus, in both approaches a relationship between local and regional-scale climate is established. Following the concept of Wigley et al., a good estimator for the Iberian local rainfall anomalies would be the anomalous spatially averaged precipitation. This approach would have failed in our case, since the area-average precipitation simulated by the GCM does not correlate with the simulated changes in the NAO index, 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 on this large scale that 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 GCMs nested into global models. 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. In the long term, the present problems 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.

Our statistical strategy offers three advantages and one limitation 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). The limitation of the statistical approach is that it can only be applied if a strong relationship between a global parameter and regional climate has been identified. Often this will not be the case.

b) Physical Aspects

The most important conclusion of this study is almost trivial: The reliability of GCM results depends on the spatial scale. For "global" spatial scales larger than $\mathcal{N}$ point distances, with $\mathcal{N} \geq 8 - 4$, the GCMs are (potentially) reliable, whereas all results on the regional scale (i.e., less than 4 grid point distances) are questionable.

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 rainfall since the beginning of this century of more than 10 mm/month, or 20-25% of its 1900-1910 level. This increasing trend is overlaid with significant variations which have a range of about 8 mm/month and a time-scale of about 20 years. In contrast, an upward trend was found in the "IPCC Scenario-A" experiment, but the strengths and the time-scales of the interdecadal variations are comparable. It should not be forgotten that the parameters entering the statistical model were fitted using data for 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 of whether they reflect interannual variability or long-term climate drifts.

The change of 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 "$2\times CO_2$"-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 positive 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 subtleties like the Iberian Peninsula, because step-function-like features (coastal mountain regions) are smoothed out and flattened by the spectral representation.

The observed rainfall trend from the beginning of this century and the prospects envisaged by the GCM experiments are not consistent. The observed data indicate a significant increase of rainfall in the last 80 years, whereas the GCM experiment predicts a decrease of Iberian rainfall.

Another aspect worth discussing is whether the questionable performance on regional scales is in contradiction to the basic assumption that the global-scale simulation is reliable. To test the sensitivity of global-scale flow to an incorrectly simulated regional climate we performed, with the ECHAM1 model, a GCM sensitivity experiment (Storch and Zorita, 1991). In the experiment, the soil evaporation at the four grid-points representing the Iberian Peninsula was, artificially, completely turned off. The GCM's response to this strong, but with respect to spatial scale small, anomaly was not statistically significant, even locally (not shown). We conclude that in the case of the Iberian Peninsula our basic assumption is not violated.

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