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An estimate of the effects of climate change on the rainfall of Mediterranean Spain by the late twenty first century

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Abstract The study uses a GCM (ECHAM-OPYC3) and the association between the atmospheric circulation at 925 and 500 hPa and the distribution of daily precipitation for Mediterranean Spain (from earlier analyses) to give estimates of the probable annual precipitation for the late twenty first century. A downscaling technique is used which involves the matching of daily circulation output from the model for a sequence of years in the late twentieth century (1971–90) and for a corresponding period in the late twenty first century (2080–99) to derive probable regional atmospheric pattern (AP) frequencies for this latter period, and thence to estimate likely changes in annual precipitation. Model days are classified by searching for the closest analogue amongst 19 previously identified APs from an earlier study. Future annual precipitation distribution is derived using previously established relationships between circulation type and daily precipitation distribution. Predicted AP frequencies and precipitation amounts and distribution are compensated by comparing model output with ECMWF data for a decade (1984–93) within the 1971–90 sequence, so that the analysis also provides a verification of the performance of the model. In general the agreement between model output and actual AP frequencies is very good for the present day, though for this southerly region the model appears slightly to under-estimate the frequency of easterly type circulations, many of which yield some of the most significant autumn severe storm rainfalls along the Mediterranean coast. The model tends to over-estimate the frequency of westerly type situations. The study utilises a 'moving window' technique in an attempt to derive measures of inter-decadal variability within the two 20 year periods. This avoids use of data from outside the periods, which would incorporate changing AP frequencies during a period of sustained climate change. Quite pronounced changes in frequency are indicated for certain APs. Marked decreases in frequency are indicated for many near-surface circulations with a westerly or northerly component. For APs with an easterly component, some are shown to increase, others to decrease. Increases in inter-decadal variability are strongly indicated for most APs, though for some easterly situations there is no clear signal. A significant annual precipitation reduction of between 6 to 14% is indicated for Andalucía and the upland parts of Cataluña. In contrast, there is an increase in annual totals of up to 14% along parts of the coast between Almería and the French border.

1 Introduction

Many General Circulation Models (GCMs) are available which permit the prediction of climates to the end of the current century. Most agree that with at least a doubling of CO_2, the most significant green house gas (GHG), during the rest of this century, marked global warming will occur in the coming decades. Models may be used to indicate future trends in precipitation as well as predicting probable future temperatures. Just as regional variation in the extent of temperature changes is anticipated through the twenty first century, so too are significant regional variations expected in precipitation: some areas becoming drier, others becoming wetter; sometimes with marked seasonal changes or shifts in precipitation pattern through the year or across a region. Many results indicate, for example, that the Mediterranean region as a whole may experience a general increase in aridity (Meteorological Office 2001; Watson and Zinyowera 2001).

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Notable recent decreases in precipitation, for example in Andalucía, have also already been noted (e.g. Esteban-Parra et al. 1998).

Such regional changes, whilst they may be averaged to a single trend for a large region such as the Mediterranean, may not necessarily be consistent across that region. Any change in the anticipated frequency and strength of westerly flows in the temperate North Atlantic, linked to changes in the North Atlantic Oscillation (NAO) and generally predicted for the coming century (Watson and Zinyowera 2001), may, for example, result in changes in precipitation receipt generally in the Mediterranean basin. This may be particularly so in the extreme west, where significant precipitation is often the result of major incursions of Atlantic flows and their embedded disturbances, and may be particularly marked during the winter (Quadrelli et al. 2001). The NAO is particularly important for Spanish rainfall (Wibig 1999). Some reports are already indicating that changes to the NAO and the mean storm track off the North Atlantic Ocean have recently taken place (e.g. Ulbrich and Cristoph 1999). In addition, changes in the oscillation have been linked closely to recent changes in Spanish rainfall (Valero et al. 1996; Esteban-Parra et al. 1998). Some studies have also linked precipitation variation in the Mediterranean region (e.g. Rodriguez-Puebla et al. 1988) and Portugal (Corte-Real et al. 1998) to the Southern Oscillation Index (SOI), though other studies for other parts of the Iberian peninsula have failed to confirm this (e.g. Quadrelli et al. 2001).

By contrast, in a study concentrating on the Mediterranean as a whole, Redaway and Bigg (1996) showed that there was a general weakening of the surface circulation between 1946 and 1987 and some increase in summer precipitation. A reduction in the incidence of westerly flows may allow for an increase in the frequency of flows from other directions, in turn increasing the incidence of mesoscale disturbances which initiate local changes in the amount, frequency, intensity and seasonal and spatial distributions of precipitation. For example, Sumner et al. (2001) indicated that for Mediterranean coastal Spain there are already signs of a shrinkage in the duration of the winter (westerly-induced) precipitation peak in Andalucía (Fig. 1), and significant seasonal changes in the occurrence and distribution of the late summer and autumn storms further east and north along the Spanish Mediterranean coast, including the Balearics. Both these trends may be linked to a change in the incidence of North Atlantic flows.

In the western Mediterranean therefore, as in other regions of the world, there is an urgent need for a downscaling of the results from GCMs so that they can be

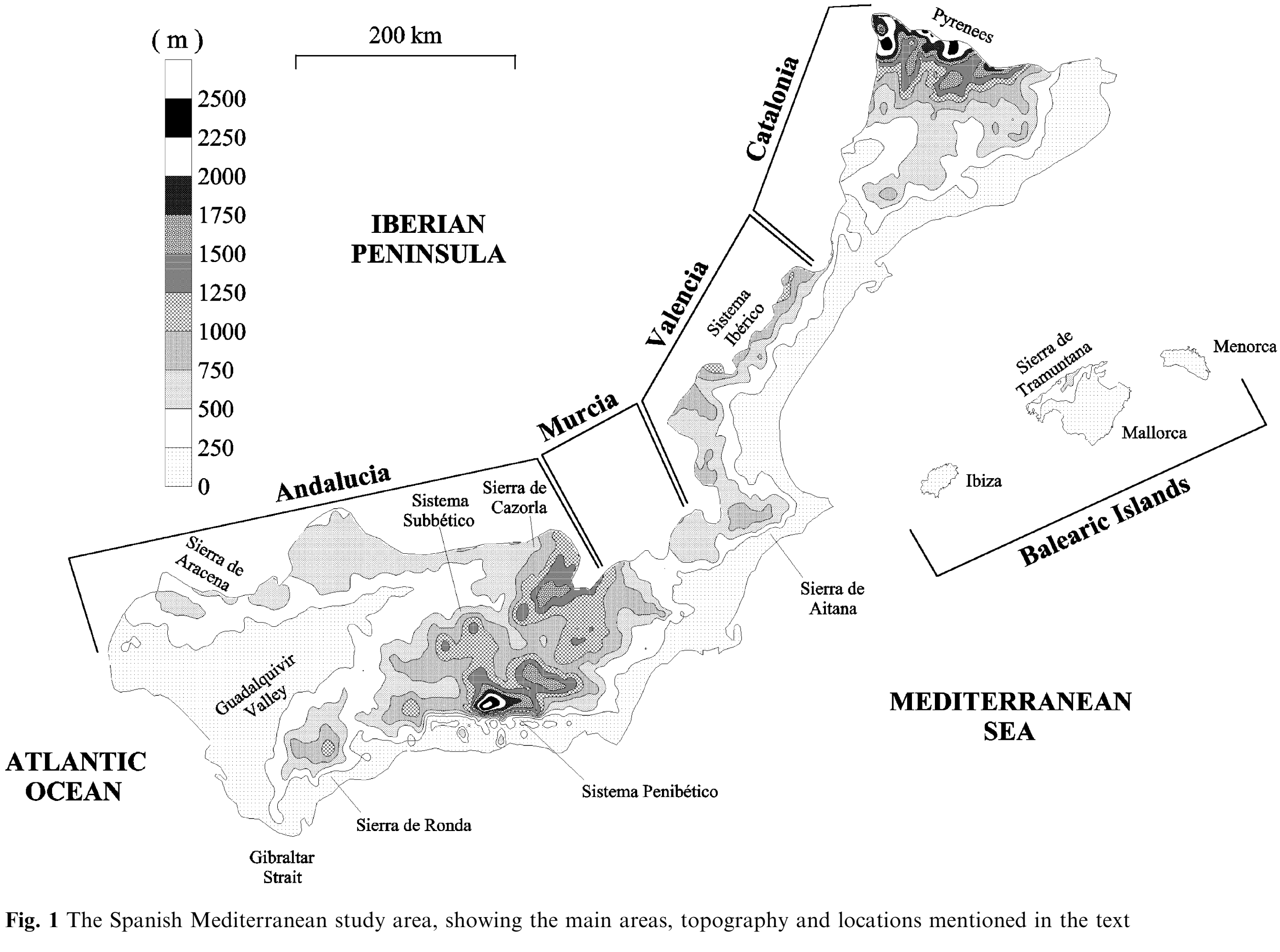


Fig. 1 The Spanish Mediterranean study area, showing the main areas, topography and locations mentioned in the text

made more directly relevant in the national, regional and local contexts. Spain is a critical area for GCM-based research (Esteban-Parra et al. 1998) because of its geographical location relative to the Mediterranean Sea, the Atlantic Ocean, and the rest of Europe. This study uses model predictions of atmospheric circulation frequencies for the last two decades of the twenty first century to provide a first estimate of likely annual precipitation amount and variability for Mediterranean coastal Spain. The use of circulation type classifications provides a highly convenient and appropriate approach to GCM down-scaling (Corte-Real et al. 1998; Goodess and Palutikoff 1998). Corti et al. (1999) clearly state that "recent climate change can be interpreted in terms of changes in the frequency of occurrence of natural atmospheric circulation regimes", so that this current approach is well-justified. It is only once this important step is made, down-scaling from regional to sub-regional, that important policy decisions may be made regarding future flood protection measures or water supply trends. The current study uses the ECHAM-OPYC3 GCM (Roeckner et al. 1998), developed at the Deutsches Klimarechenzentrum, Hamburg, and builds on, and develops further, some important earlier findings concerning the nature of the spatial distribution of precipitation in the area (Romero et al. 1998, 1999a, b; Sumner et al. 2001).

2 Established background to the study

This present study is underpinned by earlier research, which established a sequence of 11 typical daily rainfall patterns (RPs) (Romero et al. 1999a; Figs. 1, 2), and derived 19 characteristic regional atmospheric patterns (APs), based on flow at the 925 and 500 hPa levels for 'significant rainfall days' during the decade 1984–93 for Mediterranean coastal Spain (Romero et al. 1999b; Fig. 3) using European Centre for Medium-Range Weather Forecasts (ECMWF) data. A significant rainfall day was defined as one on which at least 5% of the 410 raingauge stations for which data were available from the Instituto Nacional de Meteorología, Spain, registered more than 5 mm. Rainfall patterns in the first study were derived using 3941 significant rainfall days for the three decades 1964–1993. The detailed methodologies involved in each of these studies appear in these earlier papers and are not repeated here.

The 19 APs (Fig. 3) fall into five major groups, although it should be appreciated that the patterns shown represent composites of all included in each cluster, and do not represent the most typical individual events. APs 1 to 4 and 9 comprise strong Atlantic flows, varying between southwesterly and northwesterly at both levels. Special cases of these more active APs occur in APs 16 to 19, together with APs 7 and 8. For APs 16 to 19 there is a progression from strong near-surface northeasterlies to northerlies, with the air flow often developing behind active cold fronts. On the other hand APs 7 and 8 comprise situations where a cold front, or a similar major active trough, is situated over Mediterranean Spain. The remaining APs generally comprise assorted variants of near-surface easterly situations for the study area. The exact characteristics of each and the character and distribution of the precipitation produced vary subtly from one to another. For three of the APs, surface lows are situated to the southwest of Spain, with a marked east or southeast near-surface warm advective flow along the Mediterranean coast: APs 5, 6 and 10. Variations on these patterns occur in APs 14 and 15, where the surface low is located over a larger part of southern Spain, but again a warm southeasterly flow is indicated for the Mediterranean coast. Surface lows are again located over southern Spain, but accompanied by cold cut-off features at 500 hPa, in APs 12 and 13. Finally, AP 11 again reflects situations where there is a near-surface low pressure area but this time with an upper westerly flow. Many of the situations contributing to this cluster incorporate summer-time thermal lows which have formed over the Iberian peninsula.

A close statistical relationship has been demonstrated between the RPs derived from the first study and the APs identified in the latter (Romero et al. 1999b), so that a first guess of the general spatial distribution of daily precipitation along the Spanish Mediterranean coast may be obtained from matching an individual day's 925 and 500 hPa circulations against one of the 19 APs. These relationships are summarised in Table 1, which is reproduced from Romero et al. (1999b). The current study uses these previously derived relationships in turn to attempt to first guess a down-scaled precipitation prediction for the study area for the end of the twenty first century. The study uses results from the ECHAM GCM for the North Atlantic/European region for the late twentieth century (1971–90), representing 'the present', and for the period 2080–99, representing 'the future'. The results from the empirical studies (Romero et al. 1999a, b) for the decade 1984–93 are used in conjunction with the results from ECHAM model output for 1971–90 to moderate the ECHAM model results for 2080–99. The 1984–93 decade would appear to have been comparatively representative of 'average' conditions. It was certainly more so than, say, that which preceded it, 1974–83, which was unusually dry in the western Mediterranean (Maheras 1988; Romero et al. 1998). Both 1982 and 1983 were very dry in the Balearics. In addition, though, the decade included some very remarkable wet weather, such as 1989. October of that year saw particularly severe convective storms along the Mediterranean coast of Spain, and in December there was high rainfall in Andalucía (Wheeler and Tout 1990).

Daily circulations at both the 925 hPa and 500 hPa levels for hypothetical significant rainfall days, derived from the model outputs, were allocated to one of the 19 APs, and comparisons made between present and future AP frequencies. The comparison between model output for 1971–90 and empirical data for 1984–93 permitted an assessment of the reliability of the ECHAM model output, and also the derivation of a correction factor to moderate indicated future AP frequencies. Such derived future AP frequencies were then used to deduce RP frequencies (Table 1), up-scaling the percentage results to compute a map of estimated rainfall from days with significant falls. This map in turn was up-scaled to provide first estimates of annual total rainfall, by reference to the contemporary association between annual average rainfall and the composite for all significant rainfall days.

3 The ECHAM GCM

The analysis uses some of the climate simulation output for the period 1860–2099 from the atmosphere–ocean coupled ECHAM-OPYC3 model. This is one of a number of well-established climate simulation models, whose characteristics and reliability matches those of other similar, currently available models. The T42 ECHAM4 atmospheric spectral model was used, comprising 19 vertical levels and having a horizontal resolution of about 2.8° latitude/longitude. The OPYC3 ocean model operates at the same resolution as the atmospheric model at mid-latitudes, with finer resolution in the tropics, and has 11 vertical levels. The technical details of the integration, as well as a summary of the most important results, can be found in Roeckner et al. (1998). In this experiment the model was forced with historical greenhouse gas concentrations, starting in 1860 and ending in 1990. After this year the concentrations were assumed to evolve according to the projections envisaged by the IPCC in Scenario A (IPCC 1992).

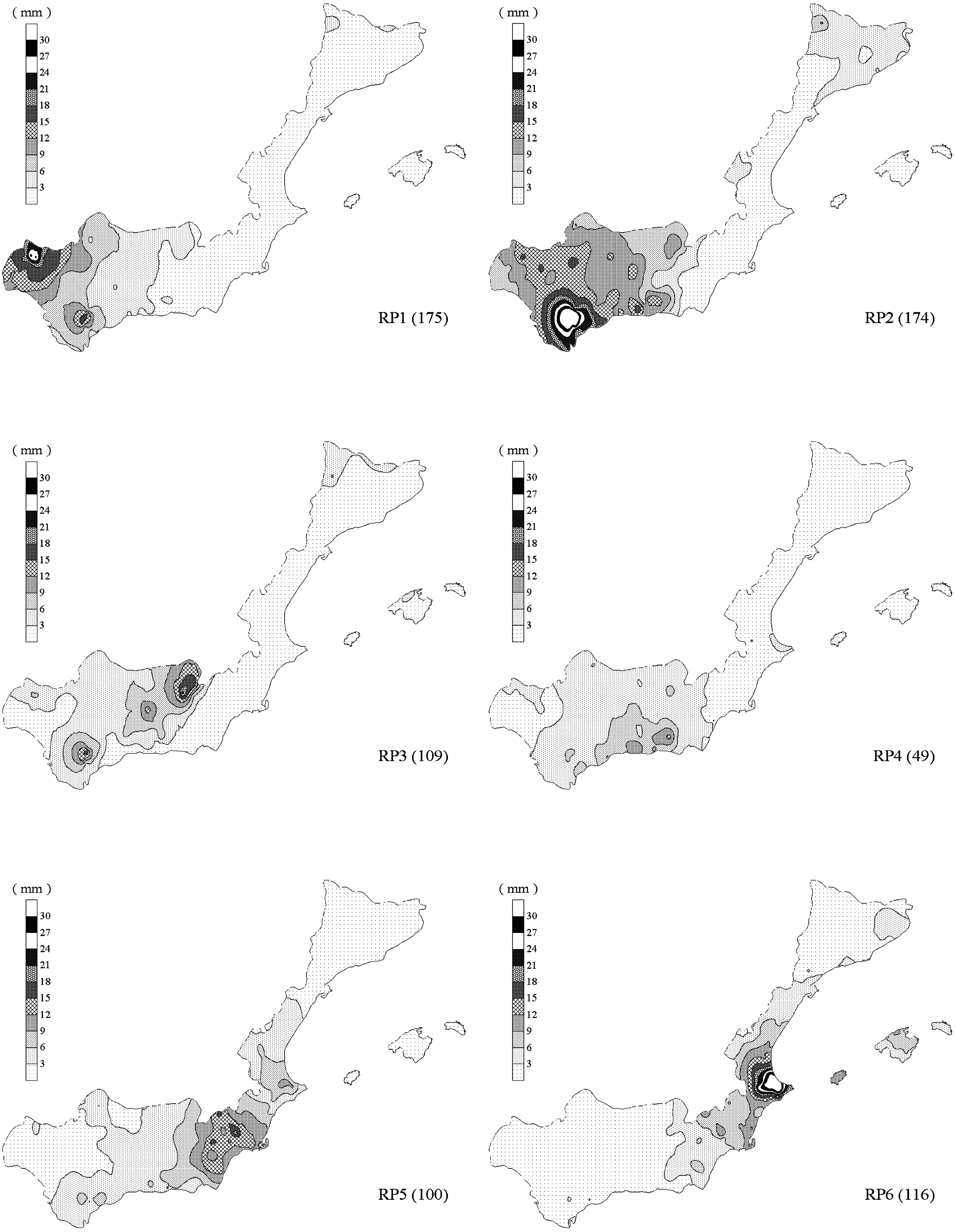
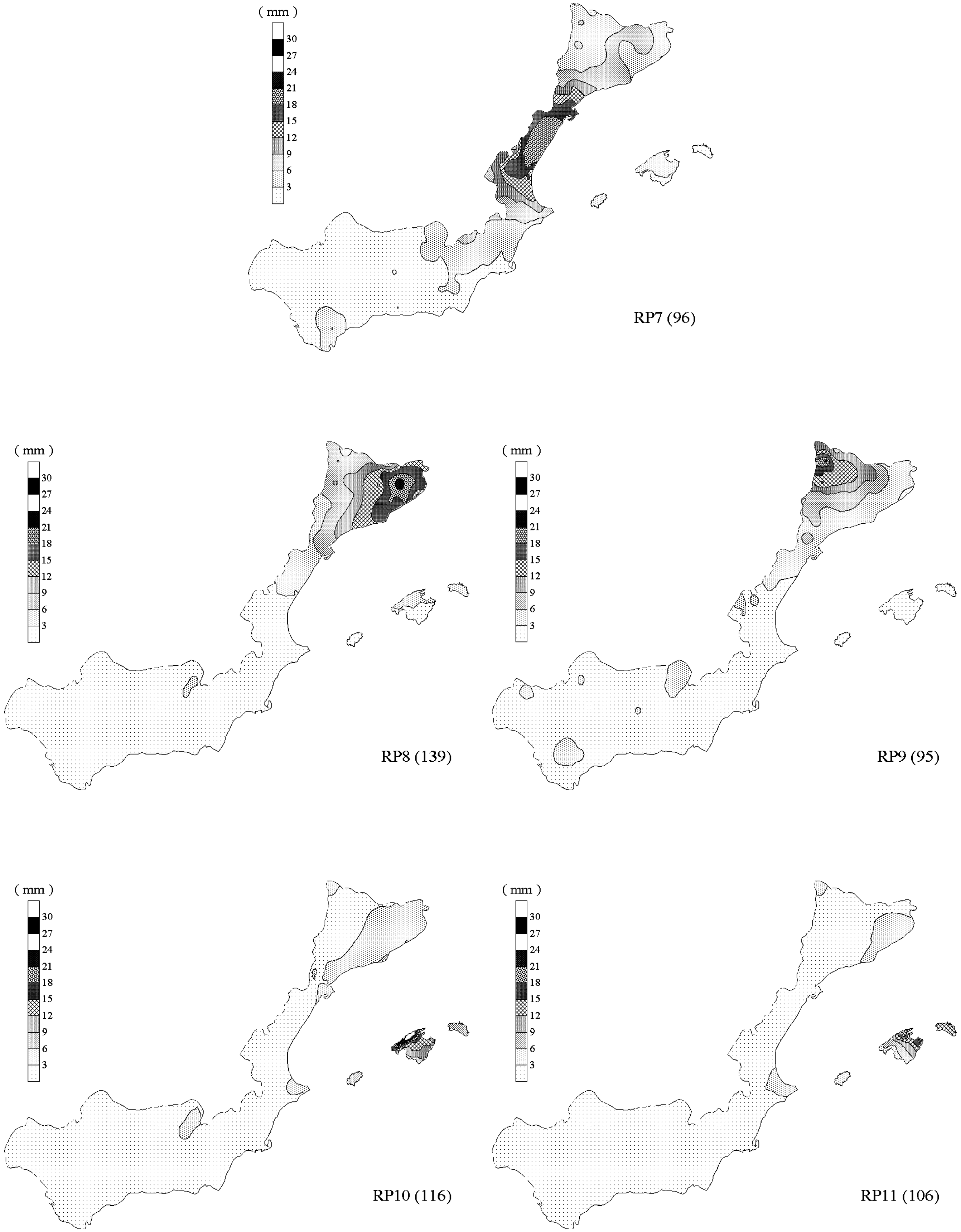


Fig. 2 Daily rainfall composites for the 11 typical patterns of significant rainfall (RPs) in Mediterranean Spain (from Romero et al. 1999a). The number of days for the decade 1984–93 (see text) included in each RP is indicated in *parentheses* (total 1275)


(mm)
30
27
24
21
18
15
12
9
6
3
RP7 (96)
(mm)
30
27
24
21
18
15
12
9
6
3
RP8 (139)
(mm)
30
27
24
21
18
15
12
9
6
3
RP9 (95)
(mm)
30
27
24
21
18
15
12
9
6
3
RP10 (116)
(mm)
30
27
24
21
18
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12
9
6
3
RP11 (106)

Fig. 2 (Contd.)

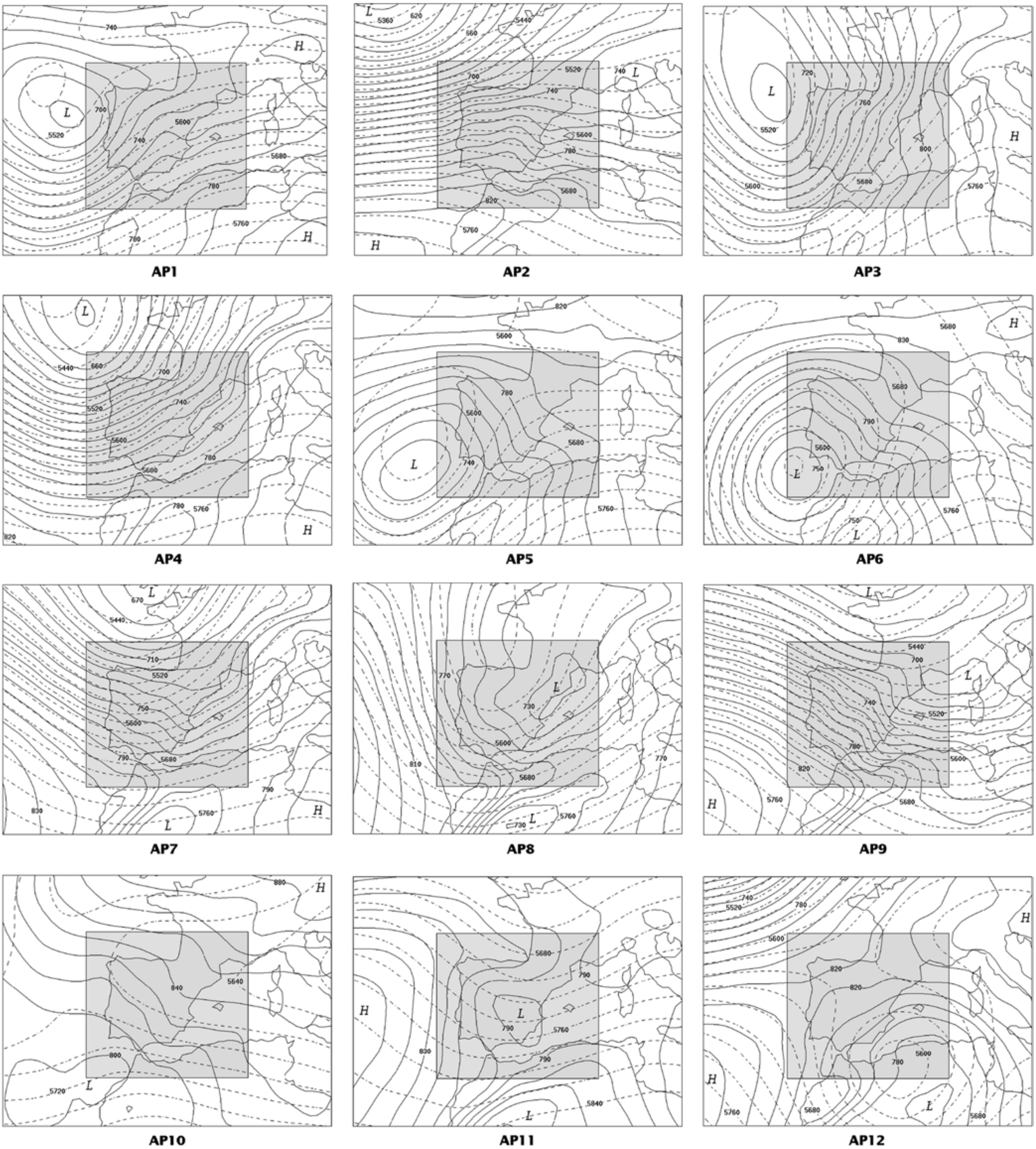
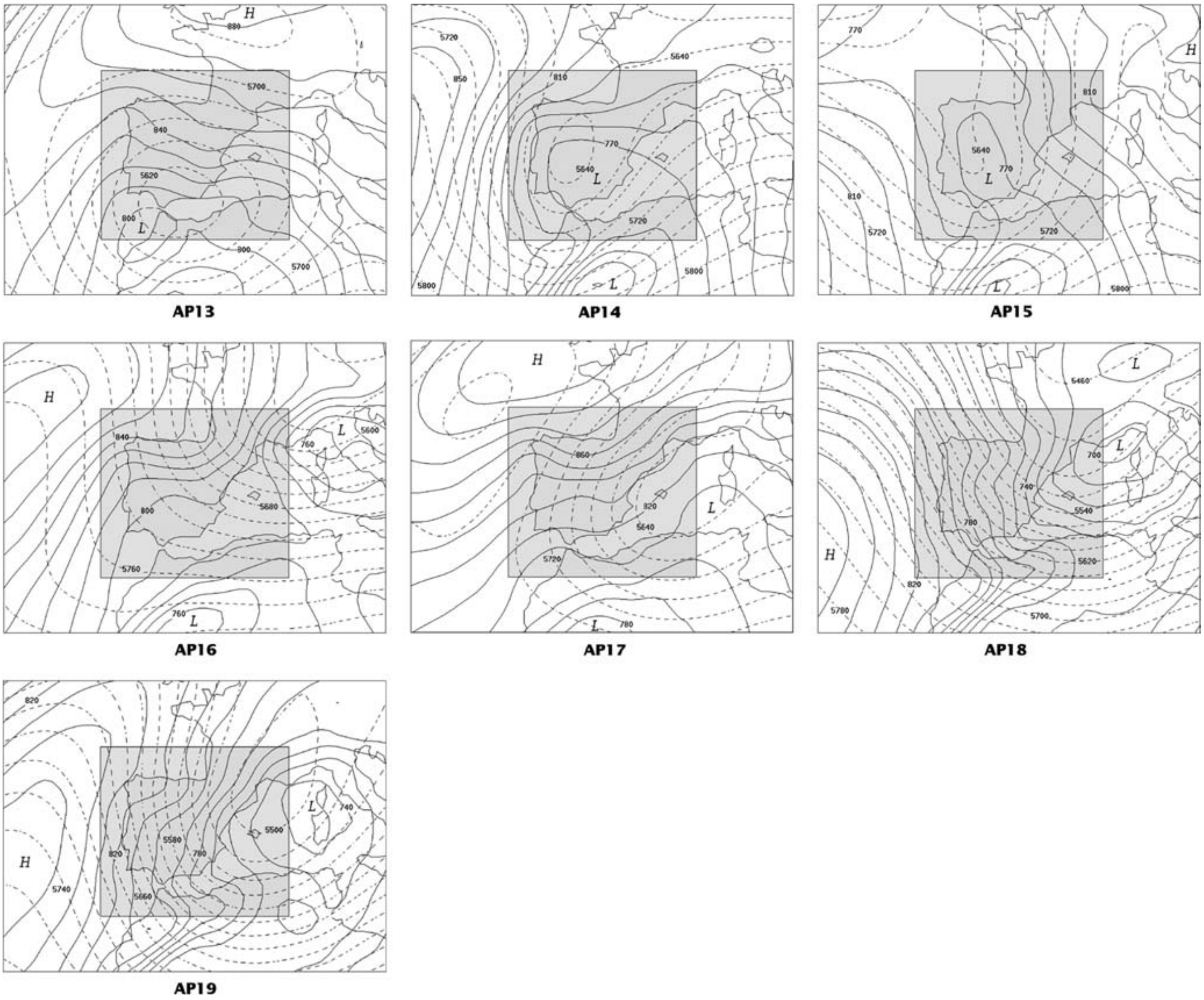


Fig. 3 Composites of the 19 APs associated with significant daily rainfall in Mediterranean Spain. The *continuous lines* represent the geopotential height field at 925 hPa (contour interval, 10 m), and the *dashed line* that at 500 hPa (contour interval, 20 m). The interior rectangle represents the geographical window used for the pattern classification (from Romero et al. 1999b)

3.1 Classification of ECHAM model daily circulation patterns

Numerous techniques exist for the matching of individual daily atmospheric patterns to the previously derived 19 ‘typical’ APs: between the two 20-year model periods, 1971–90 (‘present’) and 2080–99 (‘future’). The one which was finally chosen classified the circulation for each model day by matching it with the closest observed day within the 1984–93 ECMWF data set: an analogue procedure. If the matched day within the ECMWF set was not itself classified within one of the 19 APs then the day was rejected



AP13 AP14 AP15

AP16 AP17 AP18

AP19

Fig. 3 (Contd.)

and was not included in the ECHAM AP classification. Matching was performed by the use of a similarity index (*d*) utilising the Pearson product-moment correlation coefficients for the combined 925 (r_{925}) and 500 (r_{500}) hPa geopotential height fields:

$$d = \sqrt{((1 - r_{925})^2 + (1 - r_{500})^2)} \ ,$$

where the correlation coefficient was calculated for points within the inner square shown in Fig. 3, as used in Romero et al. (1999). Similar analogue approaches to down-scaling have been used elsewhere to good effect (e.g. Martin et al. 1997).

Since the main aim of this study is to establish future changes in AP frequencies with an acceptable degree of precision, it is important to provide a measure of confidence in the predicted results. Some measure of natural dispersion about the indicated norm is required. AP frequencies for individual decades are basically ‘snapshots’ of a moment in time, and there is no certainty that they will be representative of the true norm. In a period of sustained climate change it is not appropriate to utilise decadal data from before or after the chosen decades as controls to illustrate natural dispersion. In this study, therefore, both present and future data have been subjected to a form of analysis which permits not only a measure of mean AP decadal frequency, but also of their dispersion about that mean. For the contemporary period, 1971–90, this is carried out by using values for a moving 10-year window: 11 overlapping decades, 1971–80; 1972–81; 1973–82, etc. Examination of the AP frequencies for each of these provides some measure of natural dispersion of decadal AP frequencies, albeit imperfect because of data dependence. A mean decadal frequency may be calculated for each AP, and the decadal variation expressed as the standard deviation (σ) or the coefficient of variability (the ratio between σ and the mean) based on the overall 11-decade frequencies. These data are summarised in Table 2.

4 Comparisons between the current ECHAM decades and empirical results, 1984–1993

A critical point within this study concerns the degree to which the model results mimic reality, as reflected in the ECMWF data set for 1984–93. A model decade comprises 3600 days, whereas a calendar decade is 3652–3653 days long, but this difference is insignificant. The model generates a total of 1317.2 significant rainfall days from a total of 3600 using the moving window technique

Table 1 Percentage frequency of the 11 daily RPs within the 19 APs (in bold, percentages greater than 15%). From Romero et al. (1999b)

Atmospheric pattern (AP)	Rainfall pattern (RP)											Number of days
	1	2	3	4	5	6	7	8	9	10	11	
1	**49.0**	**33.3**	0.0	2.0	0.0	0.0	5.9	5.9	2.0	0.0	1.0	51
2	**46.5**	**23.9**	**15.5**	0.0	1.4	0.0	0.0	2.8	1.4	4.2	4.3	71
3	**35.7**	**36.9**	0.0	1.2	4.8	1.2	8.3	8.3	2.4	0.0	1.2	84
4	**30.5**	**36.2**	4.8	0.0	0.0	1.0	8.6	2.9	12.4	1.9	1.7	105
5	**22.4**	**25.9**	0.0	12.1	**15.5**	5.2	8.6	0.0	6.9	1.7	1.7	58
6	**17.9**	**15.4**	5.1	7.7	**21.8**	9.0	**17.9**	3.8	0.0	0.0	1.4	78
7	13.0	9.0	**25.0**	4.0	3.0	2.0	2.0	14.0	**25.0**	2.0	1.0	100
8	2.6	13.2	**15.8**	1.3	3.9	0.0	10.5	**23.7**	**21.1**	6.6	1.3	76
9	2.3	8.1	**41.9**	3.5	0.0	1.2	2.3	**16.3**	4.7	10.5	9.2	86
10	3.6	10.7	0.0	0.0	10.7	14.3	14.3	**28.6**	3.6	7.1	7.1	28
11	1.4	1.4	4.3	2.9	4.3	11.4	11.4	**30.0**	**20.0**	7.1	5.8	70
12	0.0	0.0	0.0	8.7	4.3	**69.6**	0.0	4.3	0.0	8.7	4.4	23
13	1.5	3.0	0.0	3.0	**28.8**	**40.9**	12.1	4.5	1.5	4.5	0.2	66
14	3.6	3.6	8.9	3.6	**17.9**	**16.1**	**21.4**	3.6	14.3	5.4	1.6	56
15	4.0	8.0	0.0	**16.0**	**20.0**	4.0	**24.0**	0.0	8.0	8.0	8.0	25
16	4.1	4.1	0.0	9.6	**16.4**	8.2	6.8	**20.5**	0.0	**17.8**	12.5	73
17	0.0	3.8	0.0	5.8	9.6	**36.5**	0.0	1.9	0.0	**19.2**	**23.2**	52
18	2.3	2.3	8.1	0.0	4.7	7.0	2.3	**17.4**	2.3	**24.4**	**29.2**	86
19	0.0	1.1	1.1	4.6	1.1	5.7	1.1	10.3	1.1	**37.9**	**36.0**	87

referred to already, against 1275 days from a total of 3653 using the ECMWF data set for 1984–93 (Romero et al. 1999b). The results appear in Table 2. Model and empirical data sets thus generate very similar sample sizes, comprising about 35% of all days, suggesting that the overall precipitation-generating potential indicated using the ECHAM GCM operates well at the regional scale and for this region. Importantly, approximately 65% of days cannot be closely matched with one of the identified 19 APs.

However, this overall good correspondence is not carried through once AP frequencies for ECMWF and model output for 1971–90 are considered. Any discrepancies must be borne in mind when interpreting the results for the future, but the ECMWF empirical data for 1984–93 may be used to provide an estimate of the reliability of contemporary model output. The degree of correspondence between the two distributions is shown in Fig. 4. Differences may vary by between 20 and 50%. From the perspective of studies in climate change of this type, however, it is the consistency in class rank order between data sets which is of greatest interest and most importance: the extent to which AP frequencies change relative to one another. For example, are the most frequent APs retained from one period to another, and are the least frequent also retained? The Spearman Rank Correlation Coefficient (r_s) is here used as a crude measure to indicate the degree of similarity between data sets. The rank correlation between the ECMWF and ECHAM 1971–90 frequencies in Fig. 4 yields $r_s = 0.8750$, which for $n = 19$ is statistically significant at much better than the 99.9% level. In most cases the difference in ranked value for AP frequency between model and empirical is two or less: the most frequent APs and least frequent APs are broadly similar. The only exceptions are for APs 1 (model rank 12, empirical rank 16), 2 (5, 10) and 6 (16, 7).

There appears to be a degree of meteorological consistency in the degree of both over- and under-estimation of AP frequencies by the ECHAM model. The model consistently under-scores for APs 5 and 6, and 10–17 inclusive (Fig. 4). All these have a strong easterly component at 925 hPa, and are generally of importance to precipitation generation in the Spanish Mediterranean in that they are frequently associated with significant or torrential rainfall events in that area (Romero et al. 1999b). By contrast, the model tends to over-score for many other circulation types, notably APs 2, 4, 7 and 9, all westerly ('Atlantic') types at 925 hPa, and APs 18 and 19, northerlies (again, essentially 'Atlantic'). It should be stressed, of course, that the model has been developed for use over large regional units, and that in the context of the larger eastern North Atlantic-European province, the western Mediterranean is exceptional in that, first, it is largely sheltered from the oceanic influence and westerlies to the west and north, and, second, it is on the far southern extremity of this westerly belt: an area where flows with a strongly negative (i.e. easterly) component are more common than for areas to the north. Also, the coarse resolution of the model could explain its relative inability to capture the characteristically small-scale Mediterranean circulations. A further important point is that any error leading the model to predict erroneously some of the transient atmospheric patterns is up-scaled into the low-frequency large-scale flow, and because this large-scale flow defines storm tracks, the APs are once again affected: a complex series of feed-backs thus operates.

5 Indicated changes in AP frequencies between late twentieth and late twenty first centuries

The ECMWF AP frequencies derived from Romero et al. (1999b), rather than the model predicted results for

Table 2 Absolute frequency (per decade) of Atmospheric Pattern (AP) types derived from ECHAM model data compared with the results of the 1999 study, using ECMWF data (after Romero et al. 1999)

Decade	Atmospheric pattern (AP)																			Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
Empirical study 1984–93, actual frequency	51	71	84	105	58	78	100	76	86	28	70	23	66	56	25	73	52	86	87	1275
ECHAM 1971–90, mean of 11 running decadal totals	45.9	108.2	82.9	141.6	42.5	26.7	140.3	77.2	131.1	17.7	59.2	7.5	48.7	36.4	14.9	62.2	42.8	126.8	104.5	1317.2
ECHAM 1971–90, standard deviation	2.3	9.7	6.1	6.2	7.2	3.9	10.3	3.0	4.8	4.8	11.9	1.8	3.7	3.4	1.7	5.2	8.0	6.2	8.0	17.5
ECHAM 1971–90, coefficient of variation (%)	5.0	8.9	7.4	4.4	17.0	14.5	7.4	3.9	3.7	26.8	20.1	23.2	7.5	9.2	11.4	8.3	18.7	4.9	7.7	1.3
ECHAM 2080–99, mean of 11 running decadal totals (uncompensated)	20.5	60.3	62.9	92.8	67.5	42.9	99.5	64.7	64.5	33.9	106.7	2.4	39.5	37.2	25.5	100.5	50.8	92.3	75.5	1139.9
ECHAM 2080–99, standard deviation (uncompensated)	2.0	11.5	7.3	5.4	10.9	4.0	14.3	6.8	4.3	4.8	13.3	1.3	7.1	6.6	3.1	12.0	6.5	7.0	6.3	21.7
ECHAM 2080–99, coefficient of variation (% – uncompensated)	9.6	19.1	11.7	5.8	16.1	9.3	14.4	10.5	6.7	14.1	12.4	54.4	18.1	17.8	12.2	11.9	12.9	7.6	8.3	1.9
ECHAM 2080–99, mean of 121 decadal totals (compensated – see text)	22.8	39.8	64.1	68.9	94.6	127.2	71.3	63.8	42.3	56.8	132.0	7.6	53.7	57.7	43.3	118.7	63.8	62.7	63.3	1254.5
ECHAM 2080–99, standard deviation (compensated)	2.4	8.1	8.6	4.8	21.4	18.4	11.2	6.9	3.1	15.4	34.9	4.4	10.2	11.0	7.0	16.5	14.1	5.5	6.9	39.1
ECHAM 2080–99, coefficient of variation (% – compensated)	10.5	20.3	13.4	7.0	22.7	14.4	15.7	10.7	7.3	27.1	26.5	58.0	19.0	19.2	16.1	13.9	22.2	8.8	10.9	3.1

1971–90, must form the basis for a comparison between contemporary and future AP frequencies. As was noted, however, there is often a notable difference between indicated AP frequencies between this empirical study and the model-generated data. In the absence of other information, it must be assumed that AP frequencies indicated by the model for future periods will differ from reality in a way similar to that noted in the previous section for the present time. The 'raw' AP mean frequencies, standard deviations and coefficients of variation for the 11 future running decades in the 2080–99 period, generated from the model by means of the technique described earlier with respect to the contemporary ECHAM model data, are shown as 'uncompensated' in Table 2. Comparison between the empirically-derived AP frequencies and the model results for the present time, however, may now be used to 'correct' future changes indicated by the ECHAM model for the period 2080–99 to take into account observed model bias. Of course, the assumption must be made that the model will continue to over- or under-estimate real AP frequencies in the future in a similar way and in similar proportions as it does at the present-time.

First, though, just as it was appropriate to attempt to derive a measure of inter-decadal AP frequency variability, described earlier, a measure of future inter-decadal variability is also required if more detailed and useful comparisons are to be made between contemporary and future situations. Again, it is inappropriate to extend the data period beyond the selected 20 years, 2080–99, to represent the late twenty first century, because the model assumes sustained GHG-induced climate change: years before the selected period will be transitional between the contemporary the future; years post-2099 will be further forced by continuing increases in GHG concentrations. Instead, future AP frequencies, compensated to take into account contemporary over- or under-estimates of real AP frequencies, have been calculated for the 2080–99 11 decadal series, 2080–89, 2081–90, 2082–91, etc. using each of the 1971–90 11 decadal series (1971–80, 1972–81, 1973–82, etc.) to define the initial criteria, yielding 121 hypothetical future decades applicable to 2080–99. A mean future frequency is subsequently calculated for each AP, together with standard deviations and coefficients of variation. If the future compensated frequency is represented by F_j, and the future 'raw' frequency is given by f_j, then the basic compensation factor (σ_j) is given by:

$$\sigma_j = E_j / M_j;$$

so that $F_j = f_j \sigma_j$;

where E_j is the absolute frequency (days) for AP_j for 1984–93; and M_j is the modelled absolute frequency (days) for a 'present' decade for AP_j.

The mean AP frequencies, standard deviations and coefficients of variation are shown as 'compensated' in Table 2. In this way it is hoped a more realistic estimate of future AP frequencies has been deduced, together

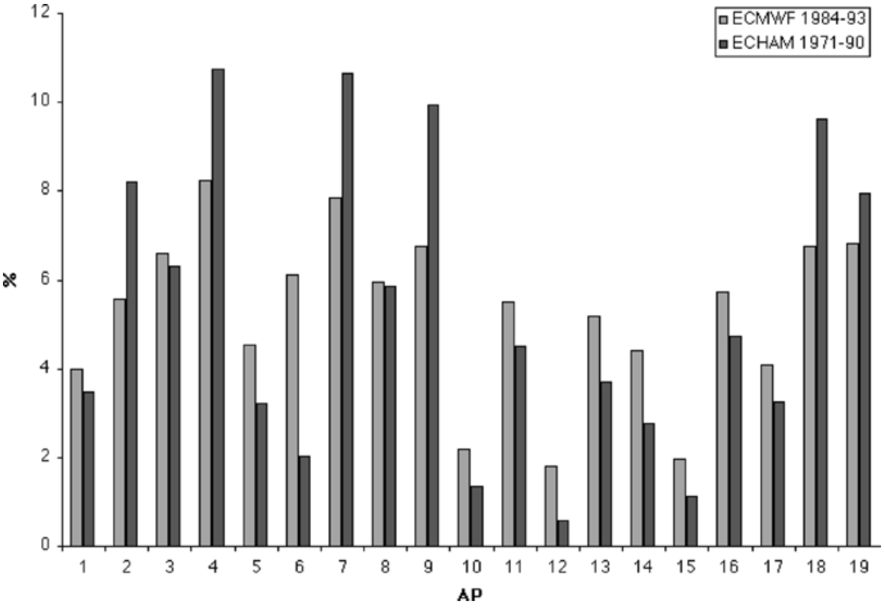


Fig. 4 Comparison between atmospheric pattern (AP) frequencies for the ECHAM model-generated decades, 1971–90 (mean 11-decade sequence; see text), and those derived from ECMWF data for 1984–93, used in Romero et al. (1999)

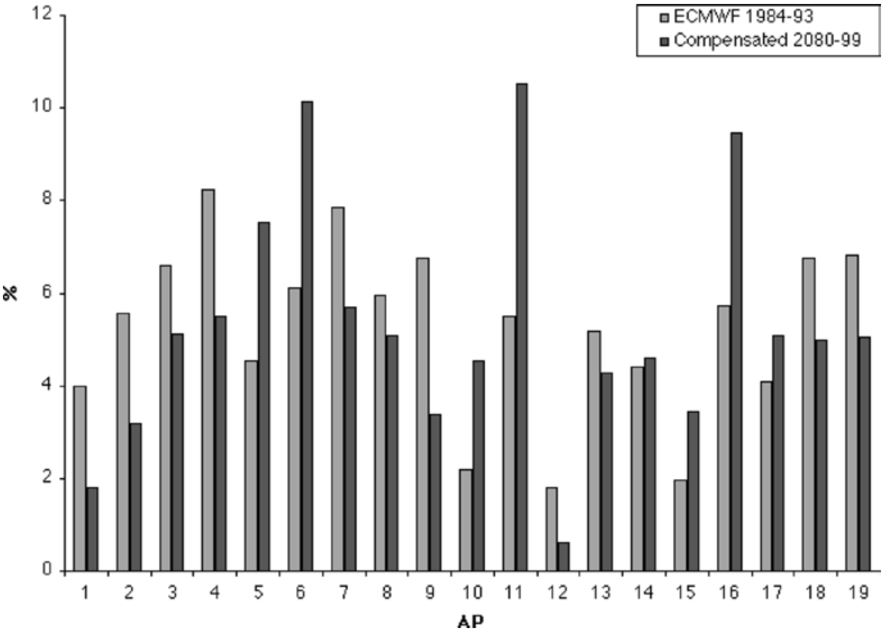


Fig. 5 Predicted (2080–99; mean 121-decade sequence) and present (based on Romero et al. 1999) AP frequencies. Predicted frequencies use results from the ECHAM model compensated with reference to contemporary model/empirical frequencies (see text)

with some estimate of possible dispersion in the data. The latter information is useful to obtain a measurement of the uncertainty associated with the signal of future precipitation changes that is being pursued in this study. It must be understood that this is an approximate value: it would be wrong to assume that the model and methodology used yield prefect results.

The future increase or decrease in frequency is thus deduced by comparing the compensated future ECHAM results with those which were derived from the empirical study using ECMWF data. These results are presented in Fig. 5. Considerable differences occur based on a comparison between the rank order of AP frequencies between present (ECMWF) and the mean future (compensated ECHAM) data sets. The Spearman Rank Correlation Coefficient (r_s) = 0.4483, which although still indicating a statistically significant relationship, but at a much reduced significance level, is equivalent to a coefficient of determination ($100r_s^2$) of only 20.1%. Notable *increases* in frequency are indicated for APs 5, 6, 10, 11, 15, and 16 (Figs. 5 and 6). In each case the percentage increase is greater than 40%. These are all examples of sustained near-surface easterly flow over the study region, or are marked by the presence of a ‘flabby’ near-surface low, such as a thermal low, over the Iberian Peninsula. APs 5 and 6 also possess a distinct upper level low to the southwest of Iberia. An increase of a lesser order is indicated for AP 17. Marked *decreases* in

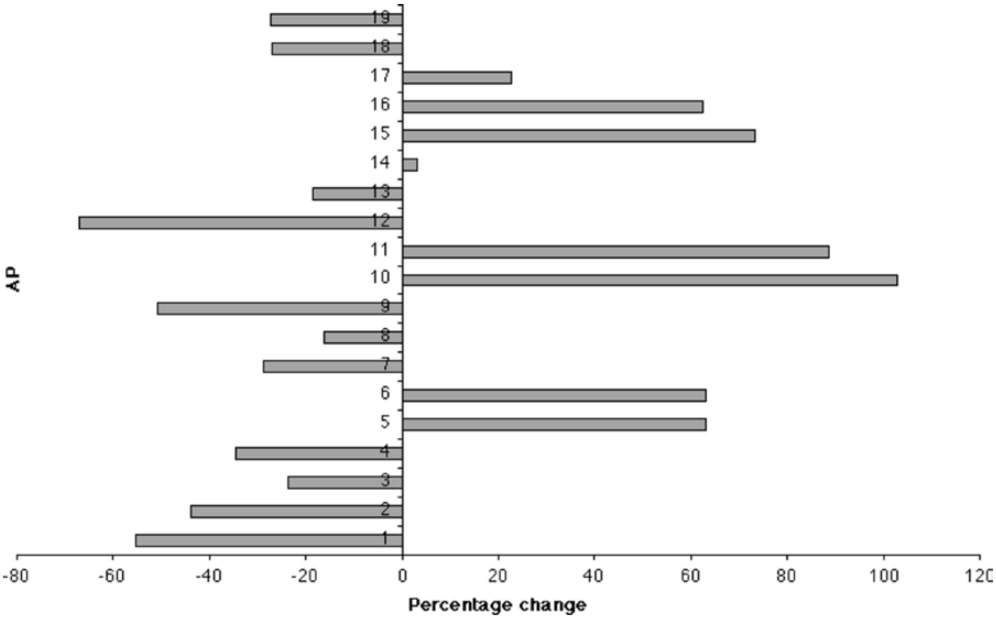


Fig. 6 Percentage changes in AP frequencies between the present day (as represented by results for 1984–93, Romero et al. 1999b) and those estimated for the last two decades of the twenty first century (using the mean 121-decade sequence for the compensated ECHAM results: see text). *Positive changes* indicate an increase in AP frequency for future decades

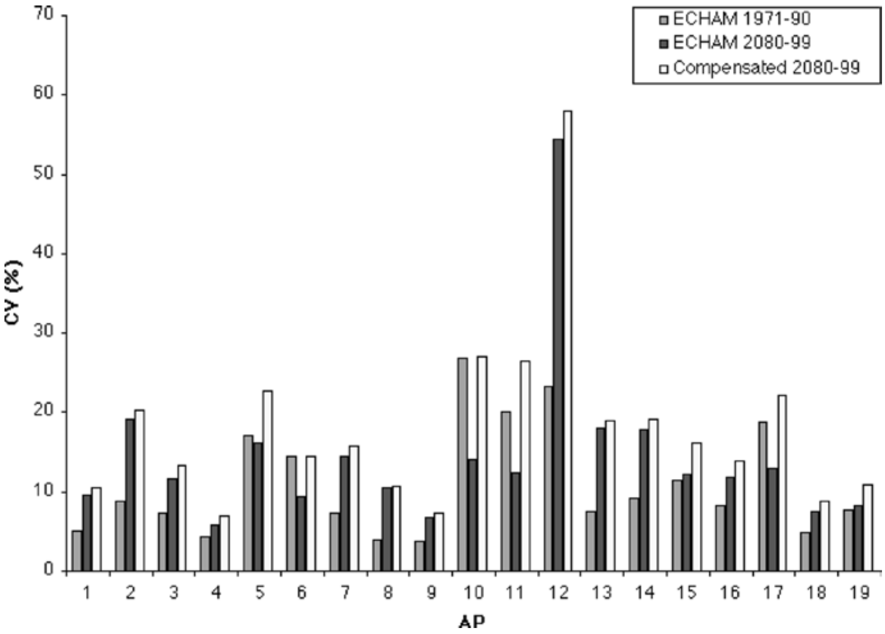


Fig. 7 Indicated changes in the coefficient of variation (CV) for the ECHAM model output for 1971–90 and 2080–99, using 11- and 121-decade sequences (see text)

occurrence are indicated for APs 1, 2, 9 and 12, with lesser decreases for APs 3, 4, 7, 8, 13, 18 and 19. APs 12 and 13 exhibit an easterly flow at 925 hPa, but with a marked cold cut-off at the 500 hPa level over or near to Iberia, in contrast to many of the easterly types for which an increasing incidence is indicated, where no such upper cut-off feature appears (APs 5, 6, 10, 11, 15, 16 and 17). The remaining APs showing a decrease in frequency all comprise westerly-type circulations, plus the two northerly types (APs 18 and 19).

Whilst it is not possible to obtain exactly equivalent dispersion information for the present (ECMWF) and future (compensated ECHAM) periods, some degree of comparison may be obtained by comparing the coefficients of variation for each AP for the 1971–90 model output with those for 2080–99 (both compensated and uncompensated), though neither is of course directly comparable with the empirical ECMWF results, for which it is anyway impossible to show decadal variability. The results shown in Fig. 7 therefore offer a rather crude measure of variability. However, they are the only ones available. For both present and future scenarios generally higher variabilities are associated with the ‘Mediterranean’ (easterly dominated near-surface circulation) than with the ‘Atlantic’ (westerly dominated near-surface circulation) flows. Caution is required, though, in the interpretation of trends where the compensation with reference to current ECMWF frequencies reverses the predicted trend. This occurs for APs 5, 6, 10, 11 and 17, where the application of the compensation factor to the results converts a decrease in dispersion into an increase. It is interesting to note that the ECHAM model has been shown above to under-estimate the incidence for all five of these APs. For the remaining five APs possessing a strong surface easterly circulation component, whose frequencies are shown to be under-estimated by the ECHAM model (APs 12, 13, 14, 15 and 16), there is a clearer indication of increasing inter-decadal variability. If a strategy is adopted of only accepting indicated increases or decreases in CVAR for an AP when this applies for *both* compensated and uncompensated results, more certainty may be assigned to changes in the coefficients of variation for the affected APs. For many of the remaining APs there is a clear, and sometimes pronounced, indication of increasing volatility in AP frequency. This is particularly the case for APs 1, 2, 7, 8, 12, 13 and 14, where a doubling in the CV is indicated. Thus, not only are quite marked changes to be anticipated in the general 'mix' of atmospheric patterns in the future when compared to contemporary frequencies, but also that there will be a considerable increase in the volatility of this mix.

6 General implications for precipitation occurrence in the late twenty first century

The characteristic rainfall patterns (RPs) derived by Romero et al. (1999a) for Mediterranean Spain were shown in Fig. 2. The associations between these and the APs derived by Romero et al. (1999b) in a later paper are shown in Table 1. The major finding of this study so far is very clear and must be stressed because of its importance for Spanish Mediterranean precipitation incidence and distribution. This is that *decreases* in AP incidence emerge for all westerly ('Atlantic') types (APs 1–4 and 7–9), for the two northerly types (APs 18 and 19), but for only two of the near-surface easterly flows (APs 12 and 13), and for one of these the decrease is small. *Increases* in incidence are indicated for most of the remaining easterly near-surface flow types, together with occurrences of a near-surface low pressure over southern or central Spain. The distinction between the two groups is thus quite clear cut, and a general important consequence for Spanish Mediterranean precipitation occurrence may be deduced at an early stage in this discussion. The simple implication of the marked decrease of westerly 'Atlantic' flows for southern Spain is that the typical atmospheric pattern producing much of Andalucía's winter and spring rainfall is decreasing and that Andalucía will suffer a decrease in overall precipitation as a consequence. APs 1–4 typically contribute a large proportion of Andalucía's total significant rainfalls. Romero et al. (1998), in their analysis of thirty years of daily rainfall from 1964 to 1993, have previously demonstrated that a clear trend towards drier conditions was already occurring in this area at the end of the twentieth century. Later, Sumner et al. (2001), using the same data set, indicated that a trend in the seasonality for this part of Mediterranean Spain is also clearly already established, with an associated reduction in the length of the winter rainfall season indicated for the first two decades of the present century. These findings are thus strongly supported by the results obtained by applying the ECHAM GCM, and lend further support for confidence in the results from the current study.

As for the APs for which an increase in incidence is indicated, the resultant effect on precipitation distribution must be slightly more complex. Easterly near-surface situations, particularly those where there is also an upper cut-off cold low, may produce some of the most significant and damaging precipitation events along much of the Mediterranean coast of Spain east of Andalucía (Table 1, Figs. 2, 3). There are conflicting signals for these important provinces along the Mediterranean coast. Most major easterly 'Mediterranean' precipitation-producing synoptic situations are increasing, although two (APs 12 and 13) are decreasing. There is thus a broad indication that the majority of such types are increasing in frequency. This will result in increased total precipitation, but together with an increase in the frequency of potentially hazardous flood-provoking torrential events (Doswell et al. 1998; Lawson 1989; Lana et al. 1995; Llasat and Puigcerver 1997; Ramis et al. 1994; Wheeler 1991). Further development of the analysis here is required if the results of this study are to be extended to quantify changes in areal precipitation receipt and provide a more detailed picture of the confidence which may be placed on the results.

7 Towards a quantified future precipitation climatology for the Spanish Mediterranean

The analysis has used empirical data only for significant rain days, defined as days on which at least 5% of the available 410 stations in the study region registered more than 5 mm precipitation (Romero et al. 1999b). The projected estimates of decadal frequency of each AP, given in Table 2, may be used in conjunction with the composite rainfalls in Fig. 2, to produce an estimate of the total precipitation from significant rainfall days per decade, by reference to Table 1. In this way a composite map may be produced showing future total precipitation from significant rainfall days per decade for the study area. This simple arithmetic process assumes, of course, that similar spatial RPs will be produced by each AP and that the contribution of each AP to RPs in the future remains very closely similar to that derived for the present time, illustrated in Table 1 (Romero et al. 1999b). The indicated frequencies of each of the 11 RPs for 2080–99 are compared with those derived from the empirical study in Fig. 8. Changes are comparatively small and involve only increases or decreases of at most one or two percentage points. However, it must be

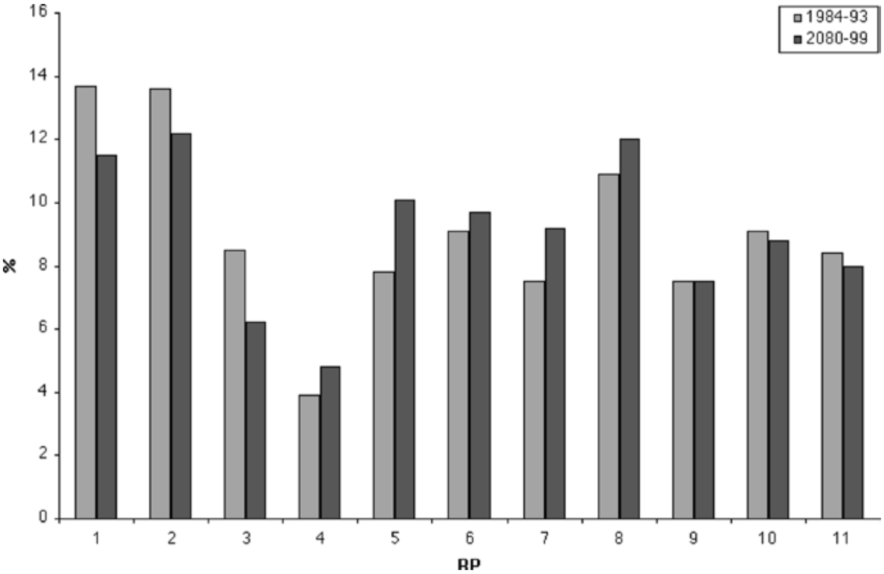


Fig. 8 Rainfall pattern (RP) frequencies from the empirical study (1984–93) and for the future (compensated ECHAM result for 2080–99 using the mean 121-decade sequence: see text)

remembered that the changes will be compounded by the amount of associated precipitation occurring over possibly more than 100 separate significant rainfall days for each AP during a decade.

A clear basic pattern may be observed in Fig. 8. RPs 1, 2 and 3 are characterised by rainfall concentrated on western and central Andalucía and upland Cataluña and in all cases there are significant decreases in frequency. There is also a slight decrease in the frequencies of RPs 10 and 11, characterised by a node of precipitation centred on the Balearics. This 'loss' of precipitation from significant rainfall days in the far south and north of the study area, and in the Balearics, is compensated by increases in the frequency of six of the other seven RPs (the frequency of RP 9 does not change), for each of which precipitation is concentrated on one of a number of comparatively small parts of the Mediterranean coast proper. These RPs are very often linked to the occurrence of severe storm development. The resultant trends are consistent: linking the shrinking incidence of westerly flows to reduced rainfall in Andalucía and other sensitive areas on the one hand; and increased incidence of many easterly flows to increased storm precipitation elsewhere.

The results so produced are of considerable interest and use, since extreme daily falls are commonly of most concern, for example as flood-producers. However, they represent only a part of the overall precipitation picture. The projections to the end of the current century must also take into account the contribution made by all other 'lesser' rain days, if they are to be of greater practical use. In some parts of the region, notably the north and especially Cataluña, there are many days with smaller amounts of precipitation. These are days which do not constitute significant rainfall days, as defined for use so far in this study and in the previous two related studies (Romero et al. 1999a, b), and have therefore been omitted from the analysis thus far. In a study dealing with the relationship between convectional and total rainfall in Cataluña, Llasat and Puigcerver (1997) showed that between 70 and 80% of all rainfall was from convective sources in the summer, but that this proportion fell to less than 30% in the winter. In many parts of the study area convection is either a major trigger in the production of a significant rainfall day, or it contributes by augmenting pre-existing precipitation-generating activity.

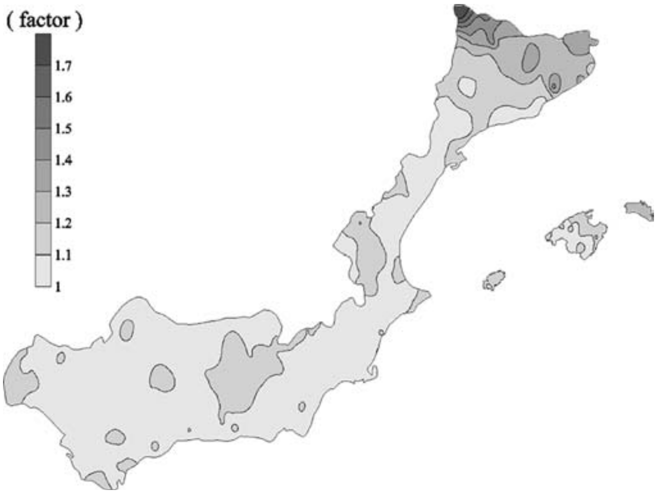


Fig. 9 The spatial distribution of the scaling factor used to estimate mean annual precipitation from significant rain day mean annual precipitation

Comparison between the significant rain day total for the empirical study decade (1984–93) and the longer term decadal mean for the same period (from Romero et al. 1998) is therefore used to deduce a simple, linear scaling factor for each gauge site in the study area (Fig. 9). This simply expresses the ratio between contemporary total annual precipitation and the amount of precipitation from significant rainfall days. The scaling factor (Φ_i) is given by:

$$\Phi_i = R_i/S_i;$$

so that $F_i = Fs_i\Phi_i$;

where R_i is the average annual rainfall for gauge i for 1984–93; S_i is the average annual (composite) rainfall for significant rain days, 1984–93 for gauge i; F_i is the corrected average annual rainfall for gauge i; and Fs_i is the total (composite) rainfall per year for significant rain days, 2080–99, derived from AP and RP frequencies for the 121 composite decades.

The factor may then be used to scale significant rain day totals for the future and arrive at an estimate of the mean annual precipitation for the study area. Figure 9 also provides important information on the extent of the contribution made by significant rain days to the total precipitation. For most parts of the study area the magnitude of the factor is very small (< 1.1), since for a majority of days on which precipitation occurs, falls are substantial. The small magnitude of the factor also suggests that application of a non-linear factor would make very little difference to the final computed results.

There is a much closer correspondence between the distribution of high factor values in the Pyrenees and relief in this northern area (Fig. 1) than in other parts of the study region. This probably reflects the greater contribution made in this area by more widespread and lower intensity precipitation, commonly associated with large-scale (e.g. Atlantic) disturbances, when compared with that from more localised, high intensity, often convectional activity. In the far north this latter contribution is relatively small. In many parts of Cataluña significant rain days contribute only about two-thirds (factor = 1.5) of the annual total. Further south very high proportions of the annual total are contributed by significant events, often associated with severe storm activity (factor close to unity). Even in Andalucía, where the westerly influence is important in the cooler half of the year, there is a strong tendency for these westerly incursions to be extreme, with large quantities of precipitation concentrated on a relatively few days. In addition, many mountainous areas, being subject to cloud, hill fog and consequent drizzle episodes, also experience a comparatively high incidence of low daily rainfall totals.

The combined application of the percentage frequency of each RP within each of the projected APs (Table 1) for the decades 2080–99, the significant rainfall composites for each RP (Fig. 2), together with the scaling factor (Fig. 9), has permitted the construction of a map of estimated mean annual precipitation for the study area for 2080–99 (Fig. 10(b) – 'future'). For comparative purposes the actual yearly mean precipitation for the decade used in the empirical study (1984–93) is also shown (Fig. 10(a) – 'present'). The confidence which may be placed on predicted future amounts and distribution is illustrated in Fig. 11, by means of the

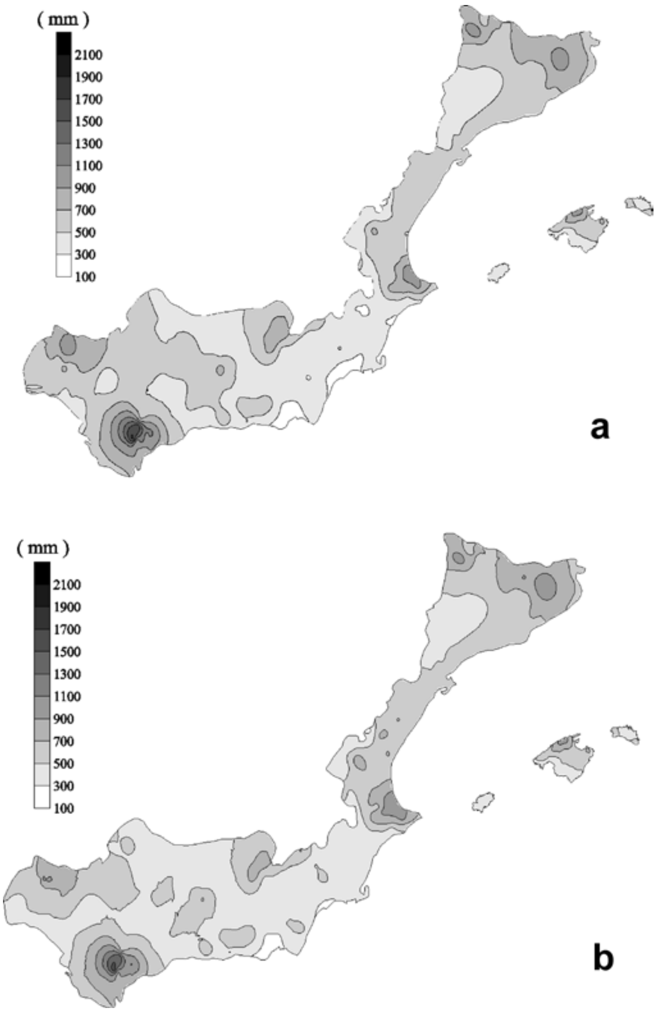


Fig. 10 **a** Actual annual mean precipitation for the decade 1984–93: 'the present'. **b** Estimated annual mean precipitation for 2080–99: 'the future'. The map portrays annual data scaled up using the scaling factor shown in Fig. 9 and the mean 121-decade sequence (see text)

Fig. 11 Predicted coefficient of variation (CV) of late twenty first century annual precipitation for the study area

coefficient of variation across the 121 hypothetical decades. It was remarked earlier that there will be markedly increased volatility in rainfall receipt at the end of the current century (Table 2; Fig. 7). The greatest degree of variability is apparent in the eastern parts of the study area, essentially from Murcia east- and northwards to Cataluña, and incorporating the Balearics. These are areas with the highest annual variability in particular of Mediterranean atmospheric circulations. The coefficients of variation are particularly high (> 5.0%) in the south of Valencia province, most of Mallorca and in the south of Menorca.

The expected percentage change in yearly total precipitation is shown in Fig. 12(a), together with the standard deviation for the change in Fig. 12(b). In this case standard deviation is a preferred measure of variability because of the double-signed field in the map of future change (Fig. 12(a)), and the very small values of the coefficient of variation near to the zero isoline. The map of the coefficient of variation of the change (not shown) is extremely noisy, and this noise masks the ease with which variability of change may be visualised from the map. Higher uncertainty of the magnitude of change is indicated, once again, for eastern and northern parts of the study area. However, whilst the greatest changes occur in Murcia and northern Valencia provinces (increase) and for western Andalucía and upland Cataluña (decrease), the greatest degree of uncertainty concerning the magnitude of the change, as represented in Fig. 12(b), occurs for Murcia, the whole of Valencia province, lowland Cataluña and the Balearics. In addition, for areas close to the zero isoline (central Cataluña and eastern Andalucía) the standard deviation far exceeds the indicated mean change, so that for a quite considerable area on either side of the zero isoline (positive and negative) little confidence may be placed in either indicated increase or decrease in precipitation. Outside these areas, though, even where indicated standard deviations are high, the anticipated mean percentage change in precipitation is also high, so that considerable confidence may be placed on the indicated changes for western Andalucía, Murcia and northern Valencia provinces.

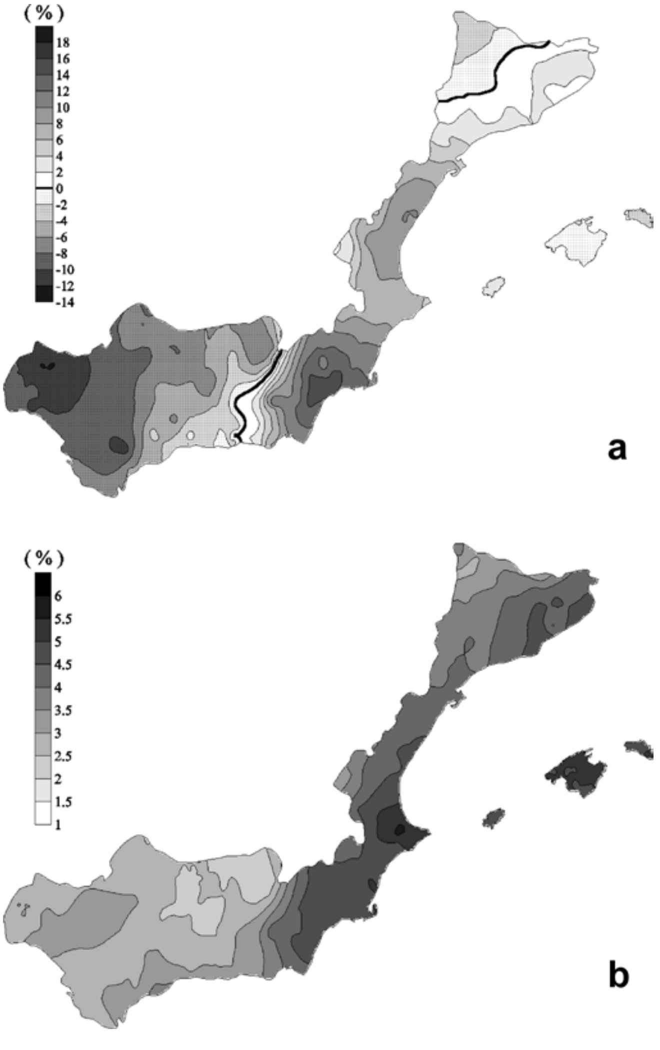


Fig. 12 a Estimated percentage increase or decrease in mean annual precipitation for the study area, 'present' to 'future', late twentieth to late twenty first centuries, and **b** its standard deviation

Very clear contrasts emerge between present and future situations. These are consistent with expectations at the larger-scale expressed by many workers in the field of climate change in the European region (Houghton et al. 2001; McCarthy et al. 2001; Meteorological Office 2001), but allow for considerable finer-scale detail to be deduced. Specifically, though, whilst a drying tendency is frequently anticipated for the whole Mediterranean region as a consequence of global warming, it is clear that whilst some areas, notably Andalucía, the mountainous parts of Cataluña, Mallorca and Menorca in this study, will in fact become drier, others, such as the major coastal embayments along the Spanish Mediterranean coast proper, for example, Almería, Murcia, Valencia, etc., together with Ibiza, will experience an overall increase in annual precipitation. The division on the map between areas with increasing and decreasing precipitation also very closely resembles that illustrated by Romero et al. (1998) in their analysis of precipitation trends through the thirty years, 1964–93, and also that produced for the area by Guijarro (2002).

Two specific areas of concern emerge from these conclusions. The first is that there is to be continued spread of aridity of the climate of the far south of Spain, extending westwards from the extreme west of Almería province to include the whole of Andalucía. This is already the hottest and one of the most arid parts of Spain, and is an area where there is great dependence on the sufficiency of the winter rains. The hottest part of the year is often almost rainless and evaporation rates are so high that they almost immediately negate any minor rainfall which does occur at this time. In some parts of the region, notably in the far west, a 12–14% decrease in annual rainfall is anticipated. Empirical analyses of current trends already indicate decreasing total rainfall (Romero et al. 1998) and a probable shortening of the winter rainfall season (Sumner et al. 2001). Using independent data, Valero et al. (1996) also showed changes in long-term precipitation seasonality over south-western Spain, specifically a reduction in winter season precipitation. Further, for the majority of Spain's Mediterranean coast east of Andalucía as far as the Ebro delta north of Valencia province, it seems likely that late summer or autumnal storms may become more frequent and perhaps more extreme, associated with an increase in the incidence of storm-generating moist 'Mediterranean' airflows. With the exception of Cataluña and the Balearics, increases in annual precipitation of between 5 and 16% are indicated for many parts of the central Mediterranean coast, and much of this may probably be attributed to a notable increase in many easterly near-surface airflows commonly associated with severe storm development.

8 Discussion

This study represents an attempt to down-scale the results from a GCM for a small part of the western Mediterranean basin, and produce a detailed map of estimated precipitation changes by the end of the century. The results seem to be in accordance both with larger-scale expectations based on earlier GCM predictions and analyses as well as with the results from empirical studies for the last three decades of the twentieth century. Indicated trends in precipitation amount and their spatial manifestation appear to be consistent with empirically derived trends and modelled future expectations. In performing the analyses in the current study five important assumptions have had to be made. The first has been that a similar relationship between APs and consequent RPs will apply in the future to that derived for the present. A further, subordinate, assumption is that similar APs will continue to deliver similar amounts of precipitation. There may be some degree of uncertainty on these points, associated with increasing absolute humidities in a warmed atmospheric environment. However, an assumption of no significant change in the relationships between amount and distribution of precipitation and atmospheric circulation has been made in other similar studies (e.g. Goodess and Palutikoff 1998). The instability inherent within many easterly near-surface flows occurring in the western Mediterranean will continue to be fed by available moisture and heat from the Mediterranean Sea and the impact of local topography and coast-line configuration in precipitation enhancement will also continue. In Andalucía any remaining westerly days in the cooler half of the year will continue to bring moisture and latent heat from the neighbouring north Atlantic Ocean. Note also that the analysis has been carried out for all seasons simultaneously, such that no seasonal differences in the AP–RP relationship are considered.

The third assumption is that the apparent minor deficiencies in ECHAM model in under-estimating easterly near-surface flow occurrence and over-estimating westerly flows for the western Mediterranean will continue, and, of course, that the inconsistencies between real and model data are not purely a consequence of selecting an 'unusual' decade, that of 1984–93, for the empirical study. This was referred to earlier in this work: 1984–93 was not an unusual decade. The presence of these differences is not in itself a particular problem, for they can be suppressed with reference to empirical data. However, the differences are themselves of importance in that they may be used to inform future model development at the lower latitude margins of the westerly belt.

Fourth, and following on directly from the third concern, it is important to point out that careful calibration was performed to ensure that the future predicted frequency distribution of APs is corrected for any differences between 'real' and model distributions at the present time. Use of the moving window technique has, for all the inclusion of a degree of data dependency within decades, provided a measure of variability to inform which indicated areas of precipitation change may be considered as likely. It has also avoided the use of control data from outside the 20-year 'snap-shots' of regional climate characteristics which would themselves be subject to the effects of continuing climate change. Finally, the fifth assumption has been that the simple scaling factor used to up-grade significant day rainfall totals to actual annual totals will also continue to be applicable.

Of course, it is possible that all five relationships may change, and perhaps the most likely is in this last case. One of the most important effects of global warming is thought to be an increase in the frequency of extreme events (at all scales, from tropical cyclones down to severe local storms) and therefore it is likely that in the future the contribution made by severe thunderstorms to Spanish Mediterranean rainfall may increase. The indicated increase in moist easterly Mediterranean flows would allow for a significant increase in this form of precipitation generation. What this study cannot anticipate, however, is whether or not either the scaling factor to up-grade significant rainfall day totals to a measure of the true annual mean will be sustained, or whether increased absolute humidities associated with a warmed world will change the amount of precipitation typically yielded for a particular area or location.

At the present time it is not possible to shed any quantitative light on these or the other assumptions made in this study. The study is a current best-guess at down-scaling future precipitation for the Spanish Mediterranean area from a GCM. The results appear to make sense and, in particular, there seems to be a close match between the conclusions here, relying on GCM predictions, and the trends demonstrated empirically elsewhere from late twentieth century data. Some confidence must therefore be ascribed to the results presented here, particularly for those areas where the variability of future precipitation change is shown to be relatively small.

Acknowledgements The authors would like to express their thanks and appreciation to the two referees of the first version of this study for stimulating a more robust analysis of the data so that the results presented have a substantially firmer basis, with a consequent greater confidence in predicted future changes. The authors also wish to acknowledge the Instituto Nacional de Meteorología (INM) of Spain for providing the ECMWF gridded data analysis, the Institut für Gewaesserphysik GKSS, Hamburg, for providing the ECHAM model output data. This work has been sponsored by CICYT grant CLI99-0269 (FIRME).

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