7. CONCLUSIONS AND FURTHER DEVELOPMENT OF THE METHODOLOGY

7.1 INTRODUCTION

During the initial stages of the thesis work, an automated circulation-typing scheme and conditional weather generator were developed and, employing output from the UKTR model, were used to construct illustrative future rain-day scenarios for the Guadalentin Basin (see Chapters 2 and 3). A number of issues raised by these initial results were discussed in Chapter 4 and were addressed further during the development of a new circulation-typing scheme (see Chapter 5) and new conditional weather generator (see Chapter 6). Output from a more recent generation of GCMs (HadCM2SUL) was used for the latter analyses. A circulation classification was constructed for three study regions forming a transect across the Mediterranean. Daily rainfall scenarios (for the number of rain days and rainfall amount) were constructed for two of these regions: the Guadalentin and Agri basins.

This chapter focuses on the issues raised in Chapters 5 and 6 and on ways in which the methodology presented in the thesis could be further refined and developed. In particular, it aims to answer the following questions:

- How do the Guadalentin and Agri study regions differ?, i.e. geographical considerations.
- Why does the downscaling method appear to work, but not always, and is it reasonable to assume that the observed circulation/surface climate relationships are stationary and will remain so in a high greenhouse gas world?, i.e. methodological considerations.
- Can the downscaling method be used to produce self-consistent scenarios for multiple sites and/or variables?, i.e. further applications of the methodology.

In addition, the extent to which the methodology meets the criteria, identified in Sections 1.1 and 1.2.1, for a good downscaling methodology is considered.

7.2 GEOGRAPHICAL CONSIDERATIONS: COMPARISON OF THE GUADALENTIN AND AGRI STUDY AREAS

The main results for the Guadalentin and Agri study areas obtained using the new circulation typing scheme and the new conditional weather generator (i.e. based on HadCM2SUL output) are summarised in Table 7.1. How do the two regions differ and to what extent are the different characteristics of the two regions reflected in the downscaling results?

While both regions have a typically Mediterranean climate regime, the

Guadalentin is considerably drier than the Agri. (This means that small sample size is likely to be a particularly severe problem for analyses in the Guadalentin. It may, for example, explain why the gamma distribution provides a less reliable description of daily rainfall distributions for the Guadalentin baseline station than for the Agri.) Both regions are characterised by very low summer rainfall, while the highest rainfall and the most frequent extreme events occur in autumn in the Guadalentin and in winter in the Agri. In the Agri, rainfall varies systematically across the basin, increasing westwards, with increasing altitude, up the valley. These strong spatial variations are reflected in the circulation type/rainfall relationships. The SW and W-types, for example, are associated with more frequent and more intense rainfall at western stations, while the E-type is associated with more frequent and more intense rainfall at eastern stations. No such systematic variation of rainfall with location/altitude is evident in the Guadalentin (which has more complex topography) and in this region the circulation/rainfall relationships are similar at all stations.

The most important high rainfall circulation types are the same in both regions (i.e. C, HYC, E and SE). The pressure patterns underlying these types are, however, different in the two regions. In the Guadalentin, for example, the underlying synoptic pattern associated with the C and HYC-types clearly resembles the Greenland above mode of the North Atlantic Oscillation (NAO). Links with the NAO appear weaker in the Agri, although variations in the strength and/or extent of the Azores High do have some influence. In the C and HYC-type composites for the Agri, for example, it is tilted to the northeast and, in winter and autumn, low pressure over the Mediterranean is squeezed between the Azores High and the Siberian High. The influence of the Siberian High is evident in many of the Agri composites (including those for the E and SE-types). In spring and summer, the low pressure over the Agri seen in the C and HYC composites may be related to the extension of the southwest Asian low-pressure system. Thus a number of large-scale influences are evident in the Agri. More local influences are also likely to be important in the Agri although it is not possible to identify individual Mediterranean cyclones because of the relatively coarse spatial resolution (i.e. 2.5° latitude by 3.75° longitude) of the classification scheme. While the influence of the NAO is evident in the composites for the cyclonic and anticyclonic circulation types in the Guadalentin, Mediterranean influences are also evident, notably in the composites for the high-rainfall E and SE circulation types. Air masses associated with these types have a long sea track across the Mediterranean and many published studies (reviewed in Chapters 3 and 5) describe the importance of such air masses for high rainfall events in southeastern Spain.

There are differences in the frequencies of the circulation types in the two regions. In comparison to the Guadalentin, the Agri has more C, HYC, UA, E, SE, S and SW-type days and fewer A, HYA, UC, N, NE, W and NW-type days. There are also differences in the seasonal cycles which may reflect the differing influences of large-scale circulation features (such as the Icelandic Low, Azores High and Siberian High) in the two regions. The C and HYC-types, for example, have a summer maximum in the Guadalentin and a summer minimum in the Agri, while the A and HYA-types have a strong seasonal cycle in the Guadalentin, but none in the Agri.

The major biases in the ability of HadCM2SUL to reproduce the observed circulation-type frequencies are similar in both regions (although stronger in the Guadalentin than the Agri), i.e. the frequencies of the C, HYC and UC-types are systematically underestimated and those of the A and HYA-types systematically overestimated. In both regions, the circulation types are less well simulated in summer than in other seasons. Overall, HadCM2SUL is somewhat less successful in the Guadalentin than the Agri (which may reflect, in part, the finding that SLP errors in winter and spring are larger over the Northeast Atlantic than over the Mediterranean). While the circulation-type errors must reflect the underlying errors in SLP, it is easier to trace them back to the errors in the flow parameters (*F*, the strength of flow and *Z*, total shear vorticity) than to the SLP errors. The strength of flow is systematically overestimated in both study regions, while total shear vorticity is significantly lower (i.e. smaller or more negative) than observed, indicating that flow is more anticyclonic than observed.

While the major discrepancies between observed and simulated circulation-type frequency are similar in both regions, the changes in SLP, and hence in circulation-type frequency, in winter and autumn at 2030-2039 and 2090-2099 are different in the two regions. In these seasons, SLP decreases over the North Atlantic to the west of the British Isles and the Iberian Peninsula and increases over the Mediterranean. This pattern of change is consistent with the decreased land/sea temperature contrast, which reflects the radiative cooling due to the direct effects of sulphate aerosols over Northern Hemisphere mid-latitude landmasses (Mitchell and Johns, 1997). The largest changes in SLP and hence in circulation-type frequency occur in winter. The increased frequency of the cyclonic circulation types and the decreased frequency of the anticyclonic circulation types in the Guadalentin in winter, and to a lesser extent in autumn, is consistent with lower SLP over the Northeast Atlantic, while the decreased frequency of the cyclonic types and the increased frequency of the anticyclonic circulation types in the Agri in these seasons is consistent with higher SLP over the Mediterranean. In spring and summer, there are small decreases in SLP over the entire Northeast Atlantic/Mediterranean area and the changes in circulation-type frequency are small and inconsistent in both regions.

These different changes in circulation-type frequency are clearly reflected in the final daily rainfall scenarios for the two regions. In both regions, the largest rainfall changes occur in winter. In this season, and to a lesser extent in autumn, rainfall increases in the Guadalentin (consistent with the increased frequency of the high-rainfall cyclonic circulation types and reinforced by the higher frequency of the high-rainfall E, SE, S and SW-types) and decreases in the Agri (consistent with the reduced frequency of the high-rainfall cyclonic and E circulation types). In spring and summer, there is uncertainty about the magnitude and even the direction of change in rainfall. Over the year as a whole, a higher percentage of significant changes in circulation-type frequency occurs for the Guadalentin than for the Agri and in, winter, the percentage changes in rainfall are higher for Alcantarilla than for Missanello.

When the succession of daily circulation-type sequences is taken from the observations, the overall performance of the new conditional weather generator (NCWG) is approximately similar for the baseline stations selected for each region (i.e. Alcantarilla for the Guadalentin and Missanello for the Agri). (Whereas, it might be expected that the performance would be worse for the drier, more extreme Mediterranean station, i.e. for Alcantarilla.) Although the percentage of runs in which the number of rain days and rainfall amount are not significantly different from observed is high for both stations (i.e. 95-100% of runs), there is a tendency for the number of rain days to be underestimated (except for Alcantarilla in summer) and for rainfall amount to be overestimated. In summer, the results are better for Alcantarilla (although it is the driest of the two stations) than for Missanello. In autumn, however, when extreme rainfall events are most likely to occur in the Guadalentin, rainfall amount is better simulated at Missanello than at Alcantarilla. Rainfall amount tends to be somewhat better simulated at both stations than the number of rain days. This is somewhat surprising because the additional probabilistic element in simulating rainfall amount, together with any shortcomings in the underlying rainfall amount categories and their representation by the gamma distribution, might be expected to result in a worse performance for rainfall amount than for the number of rain days.

At both stations (except Alcantarilla in summer, when the observed standard deviations are considerably lower than in other seasons), the simulated year-to-year standard deviations are systematically underestimated. There is not, however, any additional loss of variance when the daily succession of circulation types is taken from HadCM2SUL output rather than from the observations. The persistence of wet and dry day spells tends to be underestimated by the NCWG regardless of whether observed or simulated circulation-type sequences are used. The errors in the simulation of extreme rainfall events (i.e. annual daily rainfall maxima with return periods of 5, 10, 20 and 50 years) reflect the errors in rainfall amount. Thus, when the circulation-type sequences are taken from the observations, rainfall amount tends to be overestimated and the simulated extreme events tend to be too large for Alcantarilla, while the extremes are reasonably well simulated for Missanello (there is, however, a slight tendency to underestimate the magnitude of events with the longest return periods).

Although the performance of the NCWG is broadly similar for both stations when the circulation-type sequences are taken from the observations, and HadCM2SUL reproduces the observed circulation types somewhat better for the Agri than for the Guadalentin, daily rainfall tends to be less well simulated for Missanello than for Alcantarilla when the circulation-type sequences are taken from HadCM2SUL. The general tendency is, however, for both stations to be too dry (reflecting the underestimation of the frequency of the high-rainfall cyclonic circulation types and the overestimation of the low-rainfall anticyclonic types). The only exceptions to this general tendency are for rainfall amount at Alcantarilla in summer and autumn, which tends to be overestimated. Although more significant discrepancies in observed and simulated circulation-type frequency occur in summer than in other seasons, the poorest NCWG performance does not occur in this season (when rainfall is very infrequent). For Alcantarilla, performance is poorest in spring (when the number of rain days is underestimated in 97% of runs) and best in winter. For Missanello, the pattern is reversed: performance is poorest in winter (when the number of rain days is again underestimated in 97% of runs) and best in spring. These differences in seasonal performance may reflect the finding that HadCM2SUL overestimates SLP over the Mediterranean in winter but not in spring (affecting the results for Missanello) and underestimates SLP over the Northeast Atlantic in both seasons (affecting the results for Alcantarilla).

As noted above, the final rainfall scenarios for 2030-2039 and 2090-2099 reflect the different seasonal patterns of circulation change in the two regions. At Alcantarilla, rainfall increases in winter and autumn in both scenario decades. In spring and summer, there is a tendency for rainfall to decrease in the first scenario decade and then to increase slightly. Thus, at Alcantarilla, the rainfall scenarios indicate an increase in the strength of the seasonal rainfall cycle, particularly in 2030-2039. In most cases, the percentage changes are broadly similar for the number of rain days and rainfall amount (Table 6.30). In winter 2090-2099, however, the percentage change in the number of rain days (50%) is considerably greater than the change in rainfall amount (34%), suggesting less intense rainfall on wet days. (This is not, however, evident in the histograms of rain per rain day shown in Figure 6.9a.) At Missanello, rainfall decreases in winter and autumn and increases in spring and summer in both scenario decades, indicating a weakening in the strength of the seasonal rainfall cycle. In all cases, the percentage changes at Missanello are broadly similar for the number of rain days and rainfall amount (Table 6.31).

In winter, the direction of change indicated by the raw GCM output and by the downscaled rainfall scenarios is consistent, i.e. positive in the Guadalentin and negative in the Agri. In spring, the direction of change is again consistent, in this case positive in both regions, although there is some uncertainty about the magnitude and direction of change in the downscaled scenarios. In summer, the raw GCM changes are ambiguous, while the downscaled scenarios suggest a small positive change, although, as in spring, there is some uncertainty about the magnitude and direction of change. In autumn, the raw GCM changes are negative in both regions. This is consistent with the downscaled scenarios for Missanello, but inconsistent with those for Alcantarilla. The pattern of SLP change is similar in winter and autumn, particularly for 2090-2099 (Figure 5.58), so it is unclear why the GCM simulates a different pattern of rainfall change for the Guadalentin in these two seasons.

7.3 METHODOLOGICAL CONSIDERATIONS: PROBLEMS AND POTENTIAL SOLUTIONS

7.3.1 Introduction

The two circulation-typing schemes developed here (see Chapters 2 and 5) are flexible enough to reflect the different large-scale synoptic influences on rainfall in the two study regions. Furthermore, the circulation type/rainfall relationships reflect the strong seasonal variations which are characteristic of the Mediterranean climate regime and the systematic spatial variability of rainfall within the Agri study area. Thus in both regions, it is possible to identify strong relationships between the predictor variables (the circulation types) and the predictand variable (daily rainfall), and these relationships are supported by an understanding of the underlying physical processes (i.e. the synoptic conditions indicated by the pressure composites). Hence two of the criteria identified in Section 1.2.1 for a good downscaling scheme are fulfilled. (The first two criteria relating to the availability of appropriate observed and GCM data are also met, although it would be advantageous to use longer time series, see Section 7.3.2)

The two study regions are sensitive to regional and seasonal variations in the ability of the GCM to reproduce the observed predictor variables (i.e. the circulation types) and the final downscaled scenarios reflect regional and seasonal variations in the simulated changes in SLP, and hence in circulation-type frequency. There are, however, a number of common problems in both regions:

- Sample sizes tend to be small, i.e. the problem of sample size and data availability;
- The circulation/rainfall relationships tend to vary over time, i.e. the stationarity problem;
- Convective rainfall events are not dealt with in a physically realistic way, i.e. the convective/large-scale rainfall problem;
- Variance and persistence are too low in the time series produced by the NCWG and extremes tend to be less well simulated than mean values, i.e. the ‘overdispersion’ problem (Katz and Zheng, 1999);
- The systematic errors in the GCM can be traced through to the downscaled rainfall series, i.e. the problem of GCM reliability; and,
- Some of the scenario changes are small compared to the errors and to the raw GCM changes, and, in some cases, there is uncertainty about the direction of change, i.e. the plausibility of the scenarios.

Each of these issues is discussed below.

7.3.2 The problem of sample size and data availability

For many analyses presented in the thesis, the period of analysis is restricted to days for which both observed SLP and daily rainfall data are available. When the data are partitioned by season and circulation type, this results in small sample sizes. Some circulation types were combined in order to calculate rainfall occurrence and amount parameters for the NCWG and a cross-validation approach was used to evaluate model performance (Section 6.3), but the resulting sample sizes are still small, particularly for the rainfall amount distributions (Section 6.2).

A reduction in the partitioning of data would increase the sample sizes and a reduction in the number of weather generator parameters would also reduce the potential risk of overfitting (Zorita and von Storch, 1999). The Mediterranean climate regime is highly seasonal (Köppen, 1936) and the circulation-type/rainfall relationships identified here vary from season-to-season (Section 5.5), supporting the partitioning of data by season. Two rather than four seasons could be used, i.e. a wet season (from September through to May, for example) and a shorter dry season (from June to August). However, the distinctive seasonal characteristics of high-rainfall events, such as the intense autumn events experienced in the Guadalentin, might well be lost.

Another possibility would be to substantially reduce the number of circulation types. A distinction can be made between regional circulation classification schemes, such as that used here, which typically consistent of around 10-20 circulation types, and schemes which identify a few major (typically two to four) large-scale and very robust circulation modes (ACCORD, 2000). Work is needed to determine whether such a coarse classification scheme would be as discriminating in terms of local rainfall characteristics as the scheme used here, particularly in the Guadalentin, where the direction of surface flow is so important (Section 5.5.1).

Improvements to stochastic weather generators are being made, incorporating new, more sophisticated statistical techniques (Wilks, 1998; 1999a; 1999b). The problems relating to persistence and variability can be reduced by such new approaches (see Section 7.3.5), but they tend to have larger data requirements. In some cases, simplicity may be an advantage. Zorita and von Storch (1999), for example, demonstrate that a simple, analogue approach to downscaling can perform as well as more complex methods, including those based on neural networks.

A related issue to sample size is that of variability within each circulation type. A number of questions arise (Wilby, 1997). Are the sample sizes large enough to capture within-type variability? Is the within-type variability smaller or greater than the between-type variability? Is the within-type variability smaller or greater than the future changes? These questions have not been fully addressed in the thesis, but the extent to which within-type variability may occur in the new typing scheme is illustrated below, focusing initially on autumn high-rainfall events in the Guadalentin.

Within-type variability

High-rainfall events are particularly likely to occur on E and SE-type days in autumn in the Guadalentin (Section 5.5.1; Table 5.9). Figure 7.1 shows that there are differences in the SLP composites constructed for wet and dry E and SE-type autumn days. A wet day is defined as any day when rainfall occurs at one or more of the 22 stations. The sample sizes for these composites are shown in Table 7.2. On wet E-type days, the positive SLP anomaly is somewhat weaker than on dry days, reflecting the lower central pressure of the Azores High (Figure 7.1). A negative anomaly occurs just to the southwest of the Iberian Peninsula on wet SE-type days, but is not evident on dry SE-type days. On the latter days, the Icelandic Low is much deeper than on wet SE-type days.

Figure 7.2 demonstrates that there also differences in the composites depending on the spatial extent of rainfall, i.e. depending on whether it is wet at a few (1-3), about half (10-12) or most (> 20) of the 22 stations. These composites can be compared with those for all E and SE-type days (Figures 5.25b and 5.29b). With more spatially-extensive rainfall on E-type days, the positive anomaly over the Northeast Atlantic tends to be weaker than in the all-day composite (compare Figures 7.2a and 5.25b). The Icelandic Low is deeper and there are also differences in the shape and location of the Azores High (compare Figures 7.2b and 5.29b). With more extensive rainfall on SE-type days, the anomalies more closely resemble those in the all-day composite, although the positive anomaly is more tilted from southeast to northwest (Figures 7.2a and 5.25b). The Icelandic Low is weaker on wetter days and there is a more pronounced low-pressure trough extending out from North Africa (Figures 7.2b and 5.29b). The deepening of this low-pressure trough (reflecting the influence of the North African thermal low) occurs for both the E and SE-types on days with more spatially-extensive rainfall.

The mean pressure maps discussed above indicate stronger flow on E and SE-type days when it is wet at the majority of stations than when it is wet at only a few stations or dry everywhere (Figures 7.1b and 7.2b). This is confirmed by Table 7.2 which shows the mean values of the strength of flow (F) and total shear vorticity (Z) parameters for the composites shown in Figures 7.1 and 7.2. These parameters are larger on wet days than on dry days, indicating stronger and more cyclonic flow. They also increase in size as the number of wet stations increases (with the exception of the F parameter for the SE-type when it is wet at 10-12 stations). Thus, although the sample sizes considered here are small (a minimum of 4, Table 7.2), there is some evidence of systematic within-type variability.

In earlier sections of the thesis it was noted that the occurrence of troughs or lows at upper levels is recognised as a contributory factor, with easterly/southeasterly surface flow, for intense rainfall events in the Guadalentin (see Sections 3.3 and 5.5.1). Figure 7.3 shows that there are differences in the 500 hPa geopotential height composites constructed for wet and dry E and SE-type days in autumn. The geopotential height data used to construct these composites was taken from the same source as the SLP data, i.e. the NMC CD-ROM data set (see Section 2.1.1). Both the surface and upper-air composites are characterised by extensive positive anomalies over the Northeast Atlantic and UK (Figures 7.1a and 7.3a). Much stronger negative 500 hPa geopotential height anomalies occur to the south or southwest of the study area on wet days than on dry days (Figure 7.3a). On E-type days, these anomalies are associated with an upper-air trough extending down, southwestwards, over the Iberian Peninsula, while on SE-type days, they are associated with a cut-off low (Figure 7.3b). Thus Figure 7.3 indicates that upper-air conditions are likely to be important, and that within-type variability occurs in both upper-air and surface composites.

Finally, day-to-day variability is considered, focusing on autumn days with intensive and extensive rainfall. These are defined as days when rainfall was greater than the 95th percentile value (which ranges from 29 to 64 mm) for at least one station. Ninety-five days meet this criterion. None of these days is an A-type day, but otherwise all the other types are represented (although only one event occurs on N, S, SW, W or NW-type days). Ten or more events occurred on UC (25 events), UA (10 events) and E (19 events) type days.

SLP and 500 hPa geopotential height composites were constructed for 10 of the 95 days. Only days when it was wet at 20 or more of the 22 stations were selected. The rainfall characteristics of these 10 days are shown in Table 7.3. The selected days include E, SE, UC, HYA, HYC, UA and NE-type days. E and SE-type days were identified as high-rainfall circulation types in autumn (Table 5.9, Section 5.5.1). The SLP and 500 hPa geopotential height charts for the two selected E and SE-type events are shown in Figure 7.4. None of the other types listed above were identified as high-rainfall types in autumn (Table 5.9; Section 5.5.1). The SLP charts for these days are shown in Figure 7.5 and the 500 hPa geopotential height charts in Figure 7.6.

On all 10 selected extreme days, surface flow over the Guadalentin tends to be generally easterly or southeasterly, regardless of the actual circulation type (Figures 7.4b and 7.5b). From the SLP composites alone, however, it is not always clear why rainfall should have been so intense, although on some days there does appear to be a low pressure trough over North Africa (for example, on 19/10/72, 7/11/71, 13/10/74 and 30/09/86). However, on all 10 days, there are negative 500 hPa anomalies somewhere in the vicinity of the study area (Figures 7.4c and 7.6a). These anomalies are associated with either an upper-air trough (for example, on 19/10/73, 2/10/69, 4/10/69 and 13/10/74) or cut-off-low (for example, on 17/10/72, 18/10/72, 19/10/72 and 30/09/86) over or close to the study area (Figures 7.4d and 7.6b). Thus the charts for the selected extreme events again illustrate the importance of upper-air conditions in this region of Spain (see discussion in Sections 3.3 and 5.5.1). In some cases, upper-air flow may be more discriminating in terms of rainfall occurrence than surface flow. Romero *et al.* (1999a), for example, note that on some occasions rainfall may occur in this region with very weak flow at low levels but with cold air aloft associated with upper-air troughs or lows.

Upper-air troughs occur across the Mediterranean (Jacobeit, 1987) and are considered to be important phenomena for rainfall over Italy (Cantú, 1977). This is illustrated by the composites for the six extreme winter rainfall events in the Agri which were identified in Section 5.5.2, together with one other major event (25/11/59, on which the maximum recorded daily rainfall value occurred for three of the 11 stations). The rainfall characteristics of these seven extreme events are shown in Table 7.4. All except one of these events occurred on a HYC or SE-type day (both identified as high-rainfall winter types in Table 5.10). The SLP composites for these events are shown in Figure 7.7. Most of the 500 hPa geopotential height composites have an area of negative anomalies somewhere to the south of the Agri (Figure 7.8a), reflecting the occurrence of an upper-air trough or low (Figure 7.8b). Note, however, that the composites for the two SE-type events which occurred in December 1984 (i.e. 4/5 and 29/30) are very different, particularly for 500 hPa geopotential height (Figure 7.8).

The illustrative case studies presented above for the Guadalentin and Agri indicate that it would be worthwhile to explore ways in which upper-air circulation as well as surface flow could be incorporated into the new typing scheme. Another feature illustrated by the case studies is the occurrence of single long storm events persisting over successive days (i.e. 17-19 October 1972 in the Guadalentin and 4-5 and 29-30 December 1984 in the Agri). The ability of the weather generators to reproduce the observed persistence of wet and dry days has been considered (see Section 7.3.5), but further work is needed to see if realistic sequences of extreme days are simulated by the NCWG and to determine whether GCMs can successfully simulate the day-to-day development of the underlying synoptic systems.

7.3.3 The stationarity problem

Three aspects of the stationarity problem were identified in Chapter 4:

- Temporal variability in circulation/rainfall relationships (and hence in weather generator parameters);

- The validity of the assumption that circulation/rainfall relationships will be unchanged in the future; and,
- The effects of low-frequency forcing.

The third aspect of the stationarity problem is not taken into account by the NCWG. It concerns variability in surface climate and the underlying forcing mechanisms, i.e. the model fails to parameterise low-frequency processes (Chapter 4.6). This failure is also relevant to the overdispersion problem and hence is discussed further in Section 7.3.5. The first two aspects of the stationarity problem are considered below.

Temporal variability

The extent to which circulation/rainfall relationships vary over time is considered in Section 3.4.2 for the original typing scheme in the Guadalentin (see particularly Figure 3.10) and in Section 5.5.2 for the new typing scheme in the Agri (see particularly Figures 5.48 to 5.51). The variability over time of the NCWG rainfall occurrence and amount parameters is considered in Section 6.3.4. All these analyses indicate that the circulation/rainfall relationships, particularly those for rainfall amount, do vary over time. However, there is a considerable degree of consistency in the characteristics of the different circulation types over time. The relationships between the three rainfall amount categories, for example, are maintained from year-to-year, i.e. the scale parameter is consistently highest for the *high* rainfall amount category (Section 6.3.4). The similarity of the circulation-type/rainfall relationships in the two schemes developed for the Guadalentin (Sections 3.2 and 5.5.1), together with the general similarity of the seasonal cycles of circulation-type frequency in the two schemes (Section 5.3.4), provides support for the robustness, but not necessarily stability over time, of the relationships.

The arguments for using the longest-possible data period to calculate the NCWG parameters, rather than trying to identify a period which is considered to be most representative of future conditions, were summarised at the end of Section 6.3.4. Elsewhere, other authors have argued that if sufficiently long data series are used (i.e. several decades), they will encompass many possible situations, including those that may become more frequent in an altered climate (von Storch *et al*., 1993; Zorita and von Storch, 1999). Thus, provided that the changes in the predictor variables are not too large (see Section 7.3.7), the use of long data series may help to address the second aspect of the stationarity problem, which is discussed below.

The assumption of unchanged future circulation/rainfall relationships

Clearly this assumption cannot be fully tested. It has, however, been argued that it can be evaluated by comparing observed and GCM-simulated circulation/rainfall relationships, and downscaled and raw GCM changes in rainfall (Busuioc *et al*., 1999). The line of argument put forward by Busuioc *et al*. is as follows:

- The regression-based model for downscaling monthly rainfall at 14 Romanian stations is shown to be skilful at the present day in all seasons except spring;
- The two GCMs (ECHAM3 T21 and T42) reliably reproduce regional rainfall and the processes determining the links between rainfall and the large-scale circulation (i.e. the links in the GCM are very similar to the observed links);
- GCMs consider many more processes than the statistical downscaling model; and finally,
- If the patterns of downscaled and raw GCM changes in rainfall are similar (although the scale of the changes may be different), it can be argued that the single (i.e. the circulation/rainfall) relationship in the statistical model must continue to account for a large part of rainfall variability in the changed climate and that the observed relationship can, therefore, be used in climate-change applications.

Busuioc *et al*. note the possibility that both the GCMs and the downscaling model may be wrong, but consider it unlikely that both would give errors of the same sign (because there are so many more processes in the GCMs). They conclude that, while it cannot provide absolute proof, their study increases confidence in the assumption of unchanged circulation/rainfall relationships in the future.

Other studies indicate that circulation/rainfall relationships are reasonably well simulated for some regions in some GCMs (Corte-Real *et al*., 1999b; Osborn *et al*., 1999b; see also the discussion of UKTR output in Section 4.5). It has also been demonstrated that SLP/rainfall relationships for six USA regions are very similar in HadCM2SUL output for 1980-1989 and 2080-2089, i.e. they do not change over time in the model (Wilby and Wigley, 2000). However, the observed relationships are not well simulated for all regions or in all GCMs (von Storch *et al*., 1993; Wilby *et al*., 1998a; 1998b; Wilby and Wigley, 2000). Furthermore, downscaled changes are not always in the same direction as the raw GCM changes (see Sections 6.5.7 and 7.3.7). Thus, unless the particular GCMs used by Busuioc *et al*. can be shown to be considerably more reliable than other GCMs, it is not clear that general conclusions about the validity of the stationarity assumption can be made on the basis of this one study. The analysis does, however, provide strong support for the plausibility (see Section 7.3.7) of the monthly Romanian rainfall scenarios developed by Busuioc *et al*. (1999).

7.3.4 The convective/large-scale rainfall problem

The circulation-typing scheme developed here is based on gridded SLP which has a spatial resolution of 2.5° latitude by 3.75° longitude (Figure 5.2). This resolution (chosen to be compatible with the UKTR and HadCM2 models) is higher than that of some gridded data sets (Section 2.1.1), but is still regional, rather than local, in scale. The typing scheme enables classification of the nature (i.e. cyclonic, anticyclonic or indeterminate) and direction (with a resolution of 45°) of surface flow over each study region, but was not designed for the identification of individual weather systems (such as Mediterranean cyclones) or local convective storms.

Convective activity is an important feature of the climate of southern Spain and Italy (Cantú, 1977; Romero *et al*., 1998). Convective storms are associated with ground heating, high atmospheric moisture content and upper-air instability and are, therefore, more likely to occur in summer than other seasons (Serrano *et al*., 1999). The high-rainfall events which occur in autumn in the Guadalentin may also be convective events, with the favourable combination of topography and easterly/southeasterly surface flow providing the conditions in which they are most likely to occur (Romero *et al*., 1998; 1999a; see discussion in Section 5.5.1). Thus, some of the high-rainfall events which occur in the Guadalentin on autumn days classified as E or SE-type days may represent convective events.

Purely convective rainfall events are more localised than rainfall events associated with a frontal system, for example. For summer and autumn, Figure 7.9 shows the number of stations in the Guadalentin (out of a possible maximum of 22) where daily rainfall is greater than the 95th percentile value, plotted against the percentage of all days with extreme rainfall (defined as any day when daily rainfall is greater than the 95th percentile value (which ranges from 29 to 64 mm in autumn and from 20 to 47 mm in summer) at one or more stations – 95 days in autumn and 49 days in summer meet this criterion). In both summer and autumn, about 50% of the extreme rainfall events are restricted to one station, indicating that these events are localised and may, therefore, be convective. More spatially-extensive events tend to occur in autumn than in summer: affecting a maximum of 13 stations in autumn and a maximum of 10 in summer.

Figure 7.10 demonstrates that the spatial extent of rainfall in the Agri may vary by circulation type and by season, focusing on winter (when rainfall reaches a maximum and extreme events are most likely to occur) and summer (when convective rainfall events are most likely to occur). In each of the four examples, the number of stations (out of 11) which are wet on a particular circulation-type day is plotted against the percentage of all wet type days. On over a third of wet C-type days in winter, rainfall occurs at all 11 stations, indicating large-scale, possibly frontal, rainfall events (Figure 7.10a). On wet C-type days in summer, however, it is much more likely to be wet at only one station rather than at all stations.

The E and SE-types are high-rainfall types in winter (Table 5.10). For the E-type, it is more likely to be raining at only one station in winter rather than at all stations, whereas the SE-type events appear to be larger-scale events, affecting all stations in more than 25% of cases (Figure 7.10b). In this example, however, it is possible that the more spatially-limited distribution of rainfall on E-type days may reflect the strong east-west rainfall gradients and the spatial variability of the circulation/rainfall relationships in the basin (see Sections 5.2.2 and 5.5.2), rather than differences between convective and large-scale rainfall.

The final two examples are for the UC, A and NE-types, which are all associated with a higher than average amount of rain per rain day at Missanello in summer (Table 5.10). In winter, it never rains at more than four stations on an A-type day (Figure 5.10c), whereas in summer it may rain at up to nine stations on such days (Figure 5.10d). It is also more likely to rain at more stations on wet NE-type days in summer than in winter. The high intensity of rainfall on these three type days in summer suggests that these may be convective events, but the wider spatial distribution of rainfall on these days in summer is contradictory.

These examples demonstrate that there are differences in the spatial extent of rainfall and in circulation/rainfall relationships between the wettest season (autumn in the Guadalentin and winter in the Agri) and the driest season (summer). In both regions, for example, a different group of high-rainfall types is identified for summer than for other seasons (Tables 5.9 and 5.10; Sections 5.5.1 and 5.5.2). This is particularly the case for the Agri, where the UC, A and NE circulation-types are high-rainfall types in summer, but low-rainfall types in all other seasons (Table 5.10). The A-type is very infrequent in the Agri during summer (Table 5.8). The UC and UA-types are, however, more frequent, occurring on 66% of summer days. Together, they contribute 44 to 71% of total summer rainfall (Figure 5.43c). Surface flow is, by definition, indeterminate on these days, thus it could be concluded that rainfall is more likely to be convective than frontal on UC and UA-type days. However, upper-air conditions also need to be considered (Section 7.3.2).

SLP and 500 hPa geopotential height charts are shown in Figures 7.11 and 7.12 respectively for eight intense summer rainfall events in the Guadalentin. These days were selected from the 49 days on which rainfall exceeds the 95th percentile value at one or more station. The rainfall characteristics of the selected days are shown in Table 7.5. In many cases (particularly 25/7/86, 22/8/81 and 10/6/69), the SLP anomaly and mean patterns are very different to those of the all type-day composites (compare Figures 7.11a and 5.24, and Figures 7.11b and 5.28). In some cases, the anomaly patterns do not appear to agree with the circulation classification (Figure 7.11a). On 4/6/73, for example, positive anomalies extend over the study region, although the day is classified as a C-type day. Conversely, on 10/6/69, negative anomalies extend over the Guadalentin, but the day is classified as a UA-type day. A clearer picture, however, emerges from the 500 hPa geopotential height composites (Figure 7.12). In all eight cases, negative anomalies occur over the study region (Figure 7.12a), indicating the occurrence of either an upper-air trough (for example, on 4/6/73 and 18/6/67) or a cut-off-low (for example, on 10/6/69 and 4/6/67). Thus it cannot be assumed that the lack of a distinctive circulation pattern at the surface on a day with intense rainfall indicates a convective event. Upper-air features may be playing a stronger role on these days, particularly when rainfall is more spatially extensive (as in the summer case studies presented here, see Table 7.5). The presence of an upper-air trough or low may, however, be an indicator of atmospheric instability, which is conducive for the development of convective activity (Serrano *et al*., 1999).

The rainfall occurrence and amount parameters for the weather generator were calculated using all wet days (Section 6.2). Thus, convective rainfall events as well as larger-scale events will be represented in the downscaled rainfall time series. Further work is, however, needed to explore the extent to which there may be systematic relationships between the circulation types and convective events and to investigate whether or not it might be possible to model convective events in a more physically realistic manner. This would require development of an appropriate objective method for the automatic identification of convective rainfall events using variables which are readily available from observed data and from GCM output.

7.3.5 The overdispersion problem

An inherent problem of stochastic weather generators is that the simulated variance and the persistence of wet and dry days tend to be underestimated (Gregory *et* *al*., 1993; Wilby and Wigley, 1997; Semenov *et al*.., 1998; Wilby *et al*., 1998a; Biau *et al*., 1999; von Storch, 1999; Wilks and Wilby, 1999; see also Sections 4.4 and 6.3.1). This is referred to as the 'overdispersion' problem (Katz and Parlange, 1996; Katz and Zheng, 1999). Two main causes of this problem have been proposed (Katz and Zheng, 1999; Wilby and Wigley, 2000).

The first proposed cause is that weather generators provide inadequate representations of high-frequency variability and hence variance and persistence are underestimated. If this is the cause of the problem, possible solutions are to:

- Use a higher-order Markov Chain model (Schubert and Henderson-Sellers, 1997; Hayhoe, 2000). This has the disadvantage of increasing the number of model parameters. There is also evidence that increasing the order of the model to as high as 10 (i.e. rainfall occurrence on each day is dependent on the conditions of the previous 10 days) would still be insufficient to reproduce the observed persistence of dry-day spells in southeastern Spain (Martin-Vide and Gomez, 1999).
- Use a different distribution for rainfall amount, such as the mixed exponential distribution rather than the gamma distribution (Wilks, 1998; 1999a; 1999b). Such a change would be relatively easy to incorporate in the NCWG and may help to overcome some of the problems with distribution fitting (see Section 6.2.3).
- Use an inflation or expansion factor to increase persistence and variance (Hay *et al*., 1991; Wilby *et al*., 1994). These factors tend to be arbitrary and may adversely affect the simulation of mean values (see Section 4.4). They also make the assumption that all the variability in the predictand is related to variability in the predictor variable (von Storch, 1999; Zorita and von Storch, 1999).
- Use a noise factor to increase the variance (von Storch, 1999; Zorita and von Storch, 1999). The method of estimating noise proposed by von Storch (1999) is designed for use in linear regression models but could be adapted for use in a weather generator. It would, however, be more complicated to apply the method to daily rainfall (a non-Gaussian variable) than to normally-distributed variables.

The second proposed cause of the overdispersion problem is that variance and persistence, i.e. interannual variability and temporal persistence, are poorly simulated by weather generators because low-frequency forcing is not considered (Katz and Zheng, 1999; Wilks and Wilby, 1999). This conclusion is an extension of the finding that, due to the persistence of the circulation states, conditioning rainfall occurrence on the state of the circulation increases the temporal persistence or autocorrelation of simulated daily time series (Hughes *et al*., 1993; Katz and Parlange, 1996; Wilby, 1998; Hughes and Guttorp, 1999; Katz and Zheng, 1999; Wilks and Wilby, 1999; Zorita and von Storch, 1999). Here, it has been confirmed that conditioning rainfall occurrence and amount on the state of the circulation and on the wet/dry status of the previous day can increase persistence and variance in the simulated series to some extent, although overdispersion is still a problem (Section 6.3.3; see also Hughes *et al*., 1993; Zorita *et al*., 1995; Zorita and von Storch, 1999).

A number of additional low-frequency variables which could be used to condition the parameters of downscaling models (i.e. the model parameters are calculated separately for different states of these variables) have been proposed (Gyalistras *et al*., 1994; Wilby *et al*., 1995; Schubert and Henderson-Sellers, 1997; Wilby, 1997; Wilby 1998; Buishand and Brandsma, 1999; Wilks and Wilby, 1999):

- temperature (including sea surface temperature);
- atmospheric humidity;
- NAO index; and,
- frontal frequency.

Incorporation of such additional variables may also help to address the problem that circulation changes may not be the only forcing factor for rainfall changes. This issue is, therefore, discussed further in Section 7.3.7.

7.3.6 The problem of GCM reliability

This problem is fundamental to all approaches to downscaling, whether empirical or model-based (Section 1.2.1).

Here, it has been shown that there are differences in the SLP and circulation-type errors displayed by two different generations of the same GCM (Section 5.3.1), reflecting differences in the model parameterisations and forcings in the two experiments (Section 5.1). The main problem with the more recent model (HadCM2SUL) is that surface flow is too strong and too anticyclonic. Despite an attempt to improve performance by using varying thresholds for the unclassified circulation types (Section 5.3), the observed circulation-type frequencies are actually less well simulated by HadCM2SUL than the older model (UKTR), except in winter. This appears to contradict the general view that HadCM2 performs better than UKTR

(Johns *et al*., 1997; Corte-Real *et al*., 1999b). It does, however, demonstrate the importance of undertaking a model validation which is tailored to the particular needs of each application.

The GCM errors are evident in the downscaled rainfall time series for both regions (Section 7.2). Since the observed circulation-type frequencies are less well simulated by HadCM2SUL than UKTR, the mean number of raindays tends to be less well simulated in the simulations for Alcantarilla based on HadCM2SUL output than in those based on UKTR output. (UKTR-based scenarios were not constructed for the Agri.)

Given these errors, downscaled time series, rather than observed series, were used to provide a baseline for the climate-change scenarios, on the assumption that the errors are consistent throughout the GCM run (Section 6.4.1). The same assumption was made in order to select the ‘best’ scenarios using ranked pairs (Section 6.5.3). The finding that a particular GCM, or indeed a particular downscaling method, is skilful at the present day does not, however, guarantee that it will perform equally successfully in response to greenhouse gas forcing (Murphy, 1999). Ultimately the assumption that similar errors and levels of skill will apply in the future is un-testable.

The circulation-typing scheme used in the thesis is based on SLP, which is considered to have advantages over other surface variables as a predictor variable, including the fact that it is reasonably well simulated by GCMs, at least over some regions (see Section 1.3). It has, however, been shown that substantial improvements are needed before SLP output from GCMs can be used to construct downscaled scenarios with full confidence.

7.3.7 The plausibility of the scenarios

The magnitude of the errors identified in the predictand (here, circulation-type frequency; see Section 5.6) and in the downscaled time series (Section 6.3) in relation to the projected climate changes (Sections 6.4 and 6.5) is one factor which needs to be considered in relation to the plausibility of the scenarios (Wilby and Wigley, 1997; Schnur and Lettenmaier, 1998; Wilby *et al*., 1998a; Zorita and von Storch, 1999). Tables 5.24 and 5.25 (discussed in Section 5.7.2) indicate that in winter (and in autumn 2090-2099), the changes in frequency of the majority of circulation types are statistically significant and/or greater than the errors (Tables 5.11 and 5.12). Fewer such changes occur in other seasons. Thus, the winter (and autumn 2090-2099) scenarios might be considered more plausible and reliable than those for other seasons.

The only cases where the difference between the NCWG simulation-set means for 2030-2039, or 2090-2099, and 1970-1979 is greater than the difference between the 1970-1979 simulation-set mean and the observed value for 1970-1979 (see the first line of each case listed in Tables 6.26 and 6.27) are:

- Alcantarilla, number of winter rain days at 2090-2099;
- Alcantarilla, winter rainfall amount at 2030-2039 and 2090-2099;
- Alcantarilla, summer rainfall amount at 2030-2039 and 2090-2099;
- Alcantarilla, number of autumn rain days at 2090-2099;
- Missanello, number of winter rain days at 2030-2039 and 2090-2099;
- Missanello, number of autumn rain days at 2030-2039 and 2090-2099; and,
- Missanello, autumn rainfall amount at 2090-2099.

Thus these changes can be considered the most plausible. The plausibility of the winter and autumn changes is supported by the quantile changes shown in Tables 6.30 and 6.31 (see Section 6.5.2). For Alcantarilla, the 0.1 and 0.9 quantile changes have the same sign (positive) in winter only. For Missanello, they have the same sign (negative) in winter 2030-2039 and 2090-2099 and autumn 2090-2099.

The arguments presented above suggest that, the larger the changes in the predictand and predictor variables, particularly in relation to the errors, the more plausible the changes in the predictand variable are likely to be. However, the larger the change in the predictor, the greater the danger of extrapolating beyond the limits of the observed data and, hence, the greater the possibility that the assumption of unchanged circulation/rainfall relationships may not be valid (see Section 7.3.3).

Another consideration is the size of the predictand changes in relation to the raw GCM changes. For the HadCM2SUL-based scenarios, the downscaled scenario changes are generally smaller in percentage terms than the raw GCM changes (Section 6.5.7). Two different reasons have been suggested as to why downscaled rainfall changes are often smaller than the GCM changes (Wilby and Wigley, 1997; Wilby *et al*., 1998a; Buishand and Brandsma, 1999):

- circulation/rainfall relationships are stronger in GCMs than in the real world; or,
- rainfall changes are not driven by circulation-changes alone.

The first argument is not, however, supported by a comparison of observed and HadCM2SUL-simulated relationships between 15 potential predictor variables and daily rainfall for six locations in the USA (Wilby and Wigley, 2000). The simulated relationships with the circulation-related variables (including SLP) are weaker than observed, while the relationships with specific humidity are stronger than observed, particularly in summer. Wilby and Wigley note, however, that it may be dangerous to extrapolate these results, which are based on inter-annual variations, to the longer-term context of anthropogenic change. Further work is also needed to determine whether these findings are applicable to other regions and GCMs.

Support for the second argument comes from studies which show that observed changes in rainfall cannot always be explained by changes in circulation (Schär *et al*., 1996; Widmann and Schär, 1997; Frei *et al*., 1998; Buishand and Brandsma, 1999; ACCORD, 2000). (Note also that the NCWG has only limited success in reproducing the different rainfall characteristics of the decade 1970-1979 compared with the full data period: see Section 6.4.1).

The atmosphere has a greater capacity to hold water at a higher temperature, thus it has been argued that the two most important variables which should be incorporated in the circulation-type approach to downscaling are temperature and atmospheric humidity (Wilby and Wigley, 1997; Wilby *et al*., 1998a; Buishand and Brandsma, 1999). Incorporating these variables may also help to reduce the overdispersion problem (see Section 7.3.5).

Two different strategies for the incorporation of these additional variables into the methodology developed here can be identified and could be explored in future work:

- The first strategy would be to condition the weather generator parameters on the circulation state of each day and on an index of low-frequency variability in temperature and/or atmospheric humidity (such as the seasonal mean):
    - long data sets would be required to build the model and the existing partitioning of data would still need to be reduced in order to avoid even more severe sample-size problems (see Section 7.3.2); and,
    - a method for identifying objective and physically-realistic thresholds in the new index/indices would have to be developed.
- The second strategy would require a major modification of the method developed in the thesis in order to use the underlying air-flow indices (see Section 2.2.2), i.e. continuous rather than discrete predictor variables, together with temperature and/or atmospheric humidity in a multiple regression model:
    - the stochastic element of the weather generator simulations would be lost;
    - but discrete circulation types and composites could still be used to

explore the underlying physical relationships.

In both cases, appropriate observed and GCM data would have to be available for the additional variables and these variables should be reasonably well simulated by the GCM. These requirements are likely to be more of a problem for atmospheric humidity than for temperature.

7.4 FURTHER APPLICATIONS OF THE METHODOLOGY: THE CONSTRUCTION OF MULTISITE/MULTIVARIATE SCENARIOS

7.4.1 Introduction

In order to limit the output requiring analysis, weather generator simulations were performed for a single baseline station in each region (Section 6.1.1). Alcantarilla was selected as the baseline station in the Guadalentin because it has more rain days per year than the other stations, thus providing the largest possible, although still relatively small, sample sizes for parameter estimation. Missanello was selected for the Agri because it is centrally located in the basin and has a long record with very few missing values.

For many impact analyses, scenarios are required for a number of stations in a region and/or for additional variables. For input to hydrological models, for example, it is important that the rainfall scenarios are consistent between sites on a day-by-basis (Schnur and Lettenmaier, 1998; Semenov and Brooks, 1999) or at even higher temporal resolutions (Venugopal *et al.*, 1999). For crop models, it is more important to have scenarios of daily rainfall, temperature and radiation which are consistent on a day-by-basis at a single site (Semenov and Brooks, 1999).

7.4.2 Methods for multisite scenario construction

A number of different methods have been used to construct self-consistent multisite rainfall scenarios:

- Sampling from the observed data, conditional on the circulation state (Hughes *et al.*, 1993; Schnur and Lettenmaier, 1998; Zorita and von Storch, 1999);
- Spatially-correlated random numbers (Wilks, 1998; 1999b; 1999c);
- A spatial covariance function for the simultaneous modelling of multisite rainfall, i.e. a transformed conditional multivariate autoregressive model (Bardossy and Plate, 1992); and,
- A Polya urn model with a spatially-correlated mixed exponential distribution

for rainfall amount (Wilson *et al*., 1992).

In addition, Hughes and Guttorp (1999) suggest how a 'conditional dependence' model (based on a multivariate vector giving rainfall occurrence at a number of sites) could be incorporated into a non-homogeneous hidden Markov model (NHMM) (see Section 1.2.3). Much of the observed spatial interdependence structure of rainfall occurrence is, however, captured by the circulation states in conditionally independent NHMMs (Charles *et al*., 1999; Bellone *et al*., 2000). This partial success may arise because the circulation states in NHMMs are identified from rainfall patterns rather than from synoptic patterns (as is done here).

In a Polya urn model, rainfall occurrence at the second station in the network is dependent on the wet/dry status of the first station, rainfall occurrence at the third station is dependent on conditions at the first and second stations and so on. Thus a large number of parameters must be calculated, particularly if rainfall is also required to be conditional on circulation type. In addition, the method gives better results for higher stations in the hierarchy than for lower-order stations (Wilson *et al*., 1992). Such an approach is not, therefore, considered appropriate here. The first two approaches listed above (sampling and the use of spatially-correlated random numbers) are, however, more appropriate and are discussed below.

7.4.3 Sampling from observed data

The sampling approach is particularly applicable for use in conjunction with baseline or reference scenarios. A procedure for applying this approach to the 'best' reference scenarios for Alcantarilla and Missanello was developed by Jean Palutikof as part of the MEDALUS III project (see the final report of Module 10.2, Project 2 available online at http://www.medalus.leeds.ac.uk/index.html). The reference scenarios for 1970-1979, 2030-2039 and 2090-2099 were selected by the author of this thesis using the method described in Section 6.5.3. The scenarios ranked 989th and 979th on the basis of the mean annual number of rain days were selected for Alcantarilla and Missanello respectively.

The rainfall observations for the common data period (1958-1987 for the Guadalentin and 1956-1976 for the Agri) for the sites for which scenarios were required (six in the Guadalentin and 11 in the Agri) were formed into a single file consisting of a time series of multisite daily observations. Each day was classified according to the season (because the circulation type/rainfall relationships vary by season), circulation type and whether the day at the baseline station was wet or dry. Then, taking the selected reference scenario, each scenario day was assigned to a class on the basis of the circulation type and the rainfall state (i.e. wet or dry) at the baseline station. A random number generator was used (with replacement) to select one multisite rainfall day from the observations in that class. By repeating the process, a multisite scenario was constructed.

This method gives daily rainfall scenarios which are consistent across a number of stations (here, six in the Guadalentin and 11 in the Agri). As in all scenario construction methods based on sampling (see Section 1.2.3), the range of variability in the downscaled scenarios is constrained by the range of the observed values (Weichert and Burger, 1998). The size of the annual maximum, for example, can never be larger than the observed maximum. However, because the frequency of the circulation types varies in each scenario, the pattern and frequency of occurrence of high-rainfall events can change in the multisite scenarios. It is also possible that, if the circulation changes are large enough, the spatial correlations in the resampled series may differ from those in the observed series, whereas other methods of multisite scenario construction do not allow changes in spatial correlation (Wilks, 1998).

A potential problem with this approach to multisite downscaling is over-sampling. Here, this problem is more of a concern for the Agri (where 10 years of simulated data were selected from 17 years of observed rainfall data) than for the Guadalentin (where 10 years of simulated data were selected from 30 years of observed data). In both cases, however, the problems are exacerbated by the systematic errors in the HadCM2SUL simulation of the observed circulation-type frequencies (Section 5.6). Circulation types which are overestimated in the 1970-1979 scenarios (such as the A and HYA-types) are likely to suffer from over-sampling. However, sensitivity studies performed by Jean Palutikof and Clare Goodess as part of the MEDALUS work showed that this problem could be substantially reduced for the Agri by adopting either of two strategies. The first option is to construct 5-year rather than 10-year multisite scenarios, thus selecting 5 years of data from 17 years. The second option is to use the longest-possible observed rainfall records and hence to reduce the number of stations: eight stations in the Agri have data for 1956-1988 (Table 5.1), for example, meaning that 10 years of data could be selected from 28 years.

The main advantages of the sampling approach to multisite scenario construction are that it is computationally simple and requires little computing time. In the next section, the second approach listed above, using spatially-correlated random numbers is considered.

7.4.4 Spatially-correlated random numbers

In the NCWG, the rainfall occurrence process (and the rainfall amount on wet days) is conditional on the circulation type of each day. Thus it might be expected that the simulated time series for a number of stations in a region will be partially correlated if the NCWG is driven by identical daily successions of circulation types for each station. However, the stochastic nature of the NCWG needs to be considered. In order to explore this issue, two groups of simulations were undertaken for 22 stations in the Guadalentin area and 15 in the Agri. In both groups, the circulation types were taken from the observations and the rainfall occurrence/amount parameters were the same as those used in the scenario runs (see Section 6.2). Only one run was completed for each station. For the Guadalentin stations, each run was for the period 1958-1987. For the Agri, each run was for 1956-1988. In the first group of runs, different sequences of random numbers (i.e. uncorrelated random numbers) were used for each station in order to determine whether each day was wet or dry, and the amount of rainfall on a wet day. In the second group of runs, identical sequences of random numbers (i.e. random numbers with a correlation coefficient of 1.0) were used for each station for the rainfall occurrence process, but different sequences were used for rainfall amount (because the different rainfall probabilities at each station mean that it will not necessarily be wet or dry at all stations on a particular day).

The results from the first group of simulations (using different random numbers) are summarised in Figures 7.13 and 7.14 for the Guadalentin and Agri respectively. The scatterplots show observed versus simulated values for the mean monthly number of rain days (Figures 7.13a and 7.14a) and rainfall amount (Figures 7.13b and 7.14b).

For the Guadalentin, agreement between observed and simulated values is reasonable from November through to May, while agreement is poorer in other months. In June, for example, the number of rain days and rainfall amount tend to be underestimated by the NCWG. From July to September, these variables tend to be overestimated. The results for the Agri are somewhat better. It should, however, be noted that the results presented in Figures 7.13 and 7.14 are based on only one realisation of the weather generator for each station, rather than on many realisations as in Chapter 6.

The scatterplots for the second group of simulations (i.e. using identical random number sequences for rainfall occurrence) are broadly similar to those for the first group and are not, therefore, shown here. None of the scatterplots, however, provide information about the spatial dependence of rainfall. In order to investigate this aspect, the joint probability of it being dry at both (P00) or wet at both (P11) stations was calculated for all possible combinations of station pairs, i.e. (*n*)(*n*-1)/2. For the Guadalentin, *n* = 22 and there are 231 combinations of station pairs. For the Agri, *n* = 15 and there are 105 combinations. The joint probabilities for the Guadalentin and Agri are shown in Figures 7.15 and 7.16 respectively.

A similar pattern of P00 and P11 joint probabilities is seen in both regions. When different random numbers are used for the rainfall occurrence process at each station, the NCWG systematically underestimates the observed probabilities (Figures 7.15a and 7.16a). This indicates that using the same circulation-type sequence for each station is not enough to reproduce the observed spatial dependence of rainfall occurrence. When identical random numbers are used, however, joint probabilities are systematically overestimated (Figures 7.15b and 7.16b).

In the latter case (identical random numbers), the correlation coefficients for the random number series used for each station must be 1.0, while for the first group of simulations they will be closer to zero. Thus, using random number series with some intermediate correlation coefficient should allow better reproduction of the observed inter-station correlations. This is the approach adopted by Wilks, who has recently developed a method for generating random number series which reproduce the observed correlations for a group of stations (1988; 1999b; 1999c). The correlations between random numbers required to reproduce the observed station correlations ($w(k,l)$ for stations k and l) cannot be computed directly from the station correlations but are found empirically by stochastic simulation. A vector of random numbers, Wt, is then generated from the multivariate normal distribution with mean vector 0 and variance-covariance matrix (Ω), the elements of which are the random number correlations $w(k,l)$. The individual Wt vectors each have a standard normal distribution and can be used in a conventional Markov Chain model to simulate rainfall occurrence. For rainfall amount, the elements of the variance-covariance matrix are the spatial correlations $\xi(k,\mathrm{l})$, obtained as smooth functions of the horizontal and vertical distances between stations.

Wilks has successfully tested this methodology for a network of 25 stations in New York state (Wilks, 1998), for six groups of five stations in the USA (ranging from California and Oregon in the west to the northeast coast) (Wilks, 1999b) and for a network of 62 stations in Oregon and Idaho (Wilks, 1999c). In theory, it could be used in conjunction with the NCWG developed here in order to generate multisite rainfall time series which are consistent across the Guadalentin and Agri on a day-by-day basis, conditional on the circulation type of each day.

7.4.5 Methods for multivariate scenario construction

Where downscaled scenarios which are consistent between variables on a day-by-day basis are required for rainfall and other parameters such as maximum and minimum temperature, solar radiation, and relative humidity, a common approach is to first simulate rainfall and then to model the other variables conditional on the rainfall state of each day (Richardson, 1981; Semenov *et al*., 1998; Skiles and Richardson, 1998; Wilby *et al*., 1998b; Hayhoe, 2000). In the widely used WGEN weather generator originally developed by Richardson (1981), for example, rainfall is modelled as a first order Markov Chain process in the conventional way and then maximum and minimum temperature and solar radiation are modelled as a multivariate first order autoregressive process (Semenov *et al*., 1998; Skiles and Richardson, 1998; Hayhoe, 2000).

Wilby *et al*. (1998b) used a Markov Chain model in which the rainfall occurrence and amount parameters were dependent on the value of air flow indices to simulate daily rainfall for sites in a Japanese catchment. Daily temperature and relative humidity were then simulated using polynomial (for temperature) and linear (for relative humidity) regression equations, with the airflow indices as the predictand variables. The regression equations were calculated, and then applied, separately for wet and dry days.

A similar approach was used by Jean Palutikof and colleagues as part of the MEDALUS III project (see the final report of Module 10.2, Project 2 available online at http://www.medalus.leeds.ac.uk/index.html) in order to produce daily maximum and minimum temperature scenarios for the multisite rainfall scenarios for three stations in each study area (Alcantarilla, Alhama de Murcia and Lorca in the Guadalentin and Moliterno, Nova Siri Scalo and Stigliano in the Agri). The multisite rainfall scenarios were constructed using the sampling method described in Section 7.4.3. The temperature scenarios were based on the transfer function method described by Palutikof *et al*. (1997) and Winkler *et al*. (1997). Stepwise multiple regression was used to construct the transfer functions using daily values of free atmosphere variables (SLP, 500 hPa geopotential height, 1000-500 hPa geopotential thickness, and gradient and backward and forward tendency values of these variables) from the NMC CD-ROM data set (see Section 2.1.1) as potential predictor variables. The transfer functions were constructed separately for wet days and dry days, thus maintaining consistency between the temperature and rainfall scenarios. The use of separate transfer functions was also shown to have some 'added value', particularly for the Guadalentin sites, i.e. the variance explained by the transfer functions tended to be higher for the separate wet and dry-day equations than for the all-day equations.

A sampling approach can also be used to construct self-consistent scenarios for a number of different variables. Brandsma and Buishand (1998), for example, used a nearest-neighbour sampling method to construct daily rainfall and temperature time series for stations in the Rhine basin. Four different sampling methods were tested in which:

i. rainfall and temperature were simulated, conditional only on the circulation index for each day;
ii. rainfall and temperature were simulated, conditional on the circulation index for each day and on the simulated wet/dry status of the previous day;
iii. rainfall and temperature were simulated, conditional on the circulation index for each day and on the circulation index, simulated rainfall and temperature of the previous day; and,
iv. rainfall, temperature and the circulation index were simulated, conditional on the simulated circulation index, rainfall and temperature of the previous day.

Methods iii and iv gave more realistic autocorrelations between the simulated variables than methods i and ii. Similar methods could also be used in conjunction with the baseline rainfall scenarios developed here, although sampling problems are likely to be a problem (see Section 7.4.3).

7.4.6 Assessment of the suitability of the baseline stations

The choice of an appropriate baseline station is particularly important when it is to be used to simulate rainfall at a number of sites across the region (Section 7.3.3). Here, Alcantarilla was selected for the Guadalentin because it has the largest number of rain days. The same criterion was used by Wilson *et al.*, 1992. In the Agri, rainfall and the circulation type/rainfall relationships vary systematically across the basin (Sections 5.2.2 and 5.5.2). Thus a centrally-located station, Missanello, was chosen. In this section, the suitability of the selected baseline stations is assessed, focusing on inter-station correlations.

Inter-station correlations were plotted against inter-station distance for rainfall amount at six stations in the Guadalentin (Figure 7.17) and 11 stations in the Agri (Figure 7.18). For the Guadalentin stations, correlations were calculated over the period

1958-1987. For the Agri, the analysis period varied depending on the length of record (see Table 5.1). In the Agri, correlations decrease linearly with increasing distance between stations, as might be expected. Clear linear relationships are not evident for the Guadalentin Basin which might be due to the more complex topography of this region (see Chapter 3.1.1 and 5.2.2). This indicates that the location of a potential baseline station in relation to the location of other stations is likely to be less important for the Guadalentin than for the Agri.

Inter-station correlations were also calculated using each station as a baseline in turn, i.e. correlations between rainfall amount were calculated using all observed days with rainfall at the baseline station. Correlations for the Guadalentin and Agri stations are shown in Tables 7.6 and 7.7 respectively. In the Guadalentin, the highest single correlation of 0.57 was obtained for Totana using Fuente Alamo as the baseline. The lowest single correlation of 0.28 was obtained for Alcantarilla using Embalse de Cierva as the baseline. These individual correlations do not, however, provide a particularly useful guide to the suitability of potential baseline stations. In order to simulate rainfall equally well at each station, it is more important for a baseline station to have similar correlations with all stations rather than the highest individual correlations. The largest range of correlations (0.35 to 0.57) occurs for Fuente Alamo, while the smallest range (0.40 to 0.43) occurs for Alcantarilla (Table 7.6), supporting the selection of Alcantarilla as the baseline station for the Guadalentin. The correlations for the Agri stations (Table 7.7) are higher than those for the Guadalentin. The largest correlation range (0.34 to 0.67) occurs for Moliterno (the westernmost station). For Missanello (the selected baseline station in the Agri), the correlations range from 0.41 to 0.61. A marginally smaller range (and higher correlations) were obtained for Roccanova (0.44 to 0.63) and Senise (0.49 to 0.68). Thus either of these stations could have been used as the baseline station for the Agri. The record for Senise is, however, slightly shorter than for Missanello and Roccanova (Table 5.1) and the station actually lies to the south of the watershed boundary. Roccanova has more missing values than Missanello. Thus it is concluded that Missanello remains an appropriate baseline station for the Agri.

7.5 CONCLUDING REMARKS

The circulation-type approach to downscaling developed here has a number of advantages, which are summarised in Table 7.8. It has been tested in a very challenging, Mediterranean climatic regime and used to produce daily rainfall scenarios which are more plausible than the raw GCM changes. The Guadalentin lies in the driest region of Europe, but the method has been applied with reasonable success here, as well as in the wetter, though still Mediterranean, conditions of the Agri. In other empirical and model-based downscaling studies, the methods have performed less well in drier areas (Schnur and Lettenmaier, 1998; Semenov *et al*., 1998; Biau *et al*., 1999; Murphy, 1999) or have not been tested in such difficult conditions.

The method developed here does have some disadvantages (Table 7.8). It is affected by a number of problems which are common to all empirical approaches to downscaling: stationarity, overdispersion, data availability and the reliability of GCMs. Many of these problems are also shared by model-based (i.e. Regional Climate Model (RCM) based) approaches. The circulation-based method developed here does, however, have sufficient advantages to be worth pursuing. A number of ways in which it could be further refined and developed have been outlined in Sections 7.3 and 7.4.

The method meets many of the criteria for a good downscaling scheme identified in Chapter 1. The downscaled scenarios have a high spatial and temporal resolution. The method is relatively simple to apply and parsimonious of computer time. It is transferable between regions. It does not require excessively large amounts of observed or GCM data. Reliable and appropriate observational data sets are available for the predictor and predictand variables (although longer time series would be desirable). There are strong relationships between the predictor and predictand variables, which are largely supported by an understanding of the underlying physical processes. These relationships are generally consistent over the observed period of record, i.e. they can be considered as stationary. The assumption that these relationships will be unchanged in the future cannot, however, be fully tested. The criterion which is least-well satisfied is that the predictor variable (here, circulation-type frequency) must be reliably reproduced by GCMs. The reliability of the underlying GCM affects all empirical and model-based downscaling methods, hence further improvements in the performance of GCMs are required before any of these methods can be used with full confidence. Further testing will be necessary to see if the method developed here performs better using output from newer generations of GCMs, such as HadCM3 (Gordon *et al*., 2000).

The major aim of the thesis was to carry out an in-depth evaluation of one approach to downscaling, i.e. the circulation-type approach. This has been successfully done. However, there is also a need for comparisons of different methods. A few such studies have been undertaken recently (Cubasch *et al*., 1996; Wilby *et al*., 1996; Wilby and Wigley, 1997; Wilby *et al*., 1998a; Zorita and von Storch, 1999), including comparisons of empirical and model-based (i.e. RCM-based) methods (Bates *et al*., 1998; Mearns *et al*., 1999; Murphy, 1999) and it would be interesting to compare the methodology developed here with other approaches.

RCM-based approaches may offer the greatest long-term potential for downscaling, but still suffer from a number of technical problems (see Section 1.2.1 and Giorgi and Mearns, 1999). In particular, the length of the runs is likely to be limited. The final downscaled scenarios presented here are for 10-year periods. However, the method could easily be applied to 100 years or more of daily output from GCMs. Very much longer series could be produced by modelling the circulation-type sequences as a Markov Chain process (as in the original weather generator, Section 3.4). The probabilistic element and the low computational requirements of the method make it particularly suitable for use in climate-change impact and sensitivity studies based on ensemble-GCM runs (Mitchell *et al*., 1999; Giorgi and Franciso, 2000).

Table 7.1: Summary of results for the Guadalentin and Agri study areas. (a) rainfall regimes and the new circulation classification scheme (Chapter 5); and, (b) results from the new conditional weather generator (NCWG) (Chapter 6). Alc. = Alcantarilla. Mis =Missanello. CT = circulation type. NRD = number of rain days, AMT = rainfall amount, SD = standard deviations, LW/LD = length of the longest wet/dry day spell.

7.1a	*Guadalentin*	*Agri*
Baseline station:	Alcantarilla, altitude = 75 m. Annual rainfall = 289 mm, 48 rain days.	Missanello, altitude = 566 m. Annual rainfall = 804 mm, 88 rain days.
Seasonal cycle:	Major rainfall peak in October. Weaker secondary peak in April	November/December rainfall peak. Weaker peak in May at some stations.
Extreme rainfall events:	More occur in autumn (and summer) than in other seasons.	More occur in winter (and autumn) than in other seasons.
Spatial variability of rainfall:	No systematic relationships with latitude/longitude. Possible negative relationship with altitude.	Strong positive relationship with altitude. Strong negative relationship with longitude.
Rainfall trends:	Weak trend towards drier conditions.	Stronger trend towards drier conditions (particularly in autumn).
Grid central point:	40° N 1.88° W	40° N 16.88° E
F/Z thresholds:	Observed: $F = 4.8$, $Z = 4.2$ Simulated: $F = 6.4$, $Z = 5.5$	Observed: $F = 4.6$, Z = 4.2 Simulated: $F = 5.8$, Z = 5.6
CT frequencies:	C/HYC: summer maximum, low in winter/autumn. A/HYA: winter maximum, summer minimum. UC/UA: 38% of days. UC: stronger seasonal cycle than in Agri.	C/HYC: summer minimum, higher in winter/spring. A/HYA: no seasonal cycle. UC/UA: 43% of days. UA: stronger seasonal cycle than in Guadalentin.
Major high rainfall CTs:	C, HYC, E, SE (and to a lesser extent, UC, NE and S).	C, HYC, E, SE (and to a lesser extent, SW and W).
Underlying SLP patterns:	C/HYC: Greenland above NAO mode. A/HYA: Greenland below NAO mode. NE Atlantic blocking associated with higher rainfall. Importance of E/SE flow with a long sea-track across the Mediterranean for high rainfall events.	C/HYC: Azores High (AH) is tilted to the northeast. (Winter/autumn: low pressure squeezed between AH/Siberian High (SH). Spring/summer: extension of SE Asian low pressure system.) Influence of NAO weaker than in Guadalentin. NE Atlantic/SH blocking associated with higher rainfall. Varying influences across the basin (e.g. of the SW, W, SE CTs).
Validation of the HadCM2SUL CT frequencies:	C, HYC & UC systematically underestimated. A, HYA & UA systematically overestimated. Largest discrepancies: C & UC in summer. Number of significant differences per season: 9, 9, 12, 6. Seasonal cycles OK (except N, E, SE).	C, HYC & UC systematically underestimated. A & HYA systematically overestimated. (Less severely than in Guadalentin.) Largest discrepancies: UC in summer. Number of significant differences per season: 9, 7, 12, 8. Seasonal cycles OK (except N, SE).
HadCM2SUL CT changes:	2030-2039: 36% of changes significant. 2090-2099: 41% of changes significant. Most significant changes in winter. Winter: C, HYC, UC, E, SE, S, SW increase; A, HYA decrease – consistent with lower SLP over NE Atlantic. Similar but weaker changes in autumn. Spring & summer: lower SLP – small & inconsistent CT changes.	2030-2039: 20% of changes significant. 2090-2099: 23% of changes significant. Most significant changes in winter. Winter: C, HYC, UC, E decrease; A, HYA, UA, SE increase – consistent with higher SLP over Mediterranean. Similar but weaker changes in autumn. Spring & summer: lower SLP – small & inconsistent CT changes.

7.1b	*Guadalentin*	*Agri*
CT groups used in the NCWG:	C+HYC, A+HYA, E+SE, S+SW, W+NW	C+HYC, A+HYA, E+SE, SW+W
Gamma distribution:	Rejected in 6 out of 12 cases.	Rejected in 3 out of 12 cases.
NCWG validation, observed CTs:		
NRD & AMT	NRD & AMT well simulated in 96-100% of runs. AMT better simulated than NRD. Tendency to underestimate NRD (except in summer) & overestimate AMT. Autumn AMT: better results for Mis.	NRD well simulated in 95-100% of runs, AMT in 97-100% of runs. AMT better simulated than NRD. Tendency to underestimate NRD & overestimate AMT. Summer: better results for Alc.
SDs	For NRD, well simulated in 42-63% of cases. For AMT, 76-90%. Under-estimated (except in summer).	For NRD, well simulated in 33-95% of cases. For AMT, 52-95%. Under-estimated in all seasons.
LW/LD	Underestimated, particularly win./spr.	Underestimated, except in autumn.
Annual daily rainfall maxima	Extremes tend to be too large.	Reasonable, but slight tendency to underestimate extremes.
NCWG validation, HADCM2SUL CTs:		
NRD & AMT	NRD too low in 2% (autumn) to 97% (spring) of cases (OK in summer). AMT well simulated in 29% (spring) to 99% (winter) of cases – slightly overestimated in summer & autumn, underestimated in winter &, particularly, spring. Overall performance: worst in spring & better in winter.	NRD too low in 2% (spring) to 97% (winter) of cases. AMT well simulated in 61% (winter) to 100% (spring) of cases – underestimated in all seasons except spring. Overall performance: worst in winter & best in spring.
SDs	Too low (except in summer), but no additional loss of variance when CTs are taken from the GCM.	Too low in all seasons, but no additional loss of variance when CTs are taken from the GCM.
LW/LD	Underestimated (except summer LW).	Underestimated (except autumn).
Annual daily rainfall maxima	Overestimated.	Underestimated.
Rainfall scenarios:		
NRD/AMT changes	Wetter in winter and autumn. Spring and summer tend to be drier (2030-2039), then wetter (2090-2099).	Drier in winter and autumn. Spring and summer tend to be wetter.
LW/LD changes	Reflect NRD changes.	Reflect NRD changes.
Annual daily rainfall max. changes	Small increase in magnitude. Slightly more events tend to occur in winter.	Small decrease in magnitude. Tend to be fewer events in winter, more in spring (& summer).
0.5 quantile changes for 2090-2099 (as % of 1970-79 values):	Win. Spr. Sum. Aut.	Win. Spr. Sum. Aut.
NRD	+50%, +4%, +9%, +11%	-24%, +4%, +5%, -14%
AMT	+34%, +9%, +10%, +5%	-31%, +6%, +4%, -19%
Raw GCM changes in AMT:	Wetter in winter (consistent with downscaled scenarios). Wetter in spring & drier in autumn. Non-systematic changes in summer. % changes greater than in downscaled scenarios (except in winter, 2030-2039).	Drier in winter, wetter in spring & drier in autumn (consistent with downscaled scenarios). Non-systematic changes in summer. % changes greater than in downscaled scenarios (except in winter 2030-2039 & 2090-2099 and autumn 2090-2099).

Table 7.2: Mean values of the strength of flow (*F*) and total shear vorticity (*Z*) parameters for the Guadalentin autumn composites for the E and SE-types shown in Figures 7.1 and 7.2. The number of days (*N*) used to construct each composite is also shown.

	Wet days	*Dry days*	*Wet at 1-3 stations*	*Wet at 10-12 stations*	*Wet at more than 20 stations*
E-type					
F	6.7	5.6	6.4	7.1	7.4
Z	2.9	2.1	2.5	2.5	4.0
N	41	8	8	4	13
SE-type					
F	6.7	5.8	6.1	5.4	6.4
Z	2.7	1.5	1.6	2.0	2.3
N	27	7	4	4	7

Table 7.3: Observed daily rainfall (mm) at 22 Guadalentin stations for the extreme autumn events shown in Figures 7.4 and 7.5. The number of stations at which rainfall is greater than 0 mm, 40 mm and the 95th percentile value is shown at the bottom of the table, together with the maximum (max.) recorded value for each day.

	19/10/73	19/10/72	2/10/69	4/10/86	4/10/69	7/11/71	17/10/72	18/10/72	13/10/74	30/09/86
Station	E	SE	UC	UC	HYA	HYC	UA	UA	NE	NE
1	1.0	60.6	33.9	85.1	27.0	3.0	50.7	49.5	32.0	30.1
2	50.0	30.0	52.0	45.0	31.0	65.5	52.0	13.0	23.0	51.0
3	30.5	95.2	33.2	67.0	12.7	35.0	29.5	0.0	8.3	43.5
4	4.0	75.0	50.0	53.0	54.0	11.2	94.0	10.0	33.0	9.0
5	90.0	10.3	86.4	29.8	28.2	45.3	27.2	1.4	26.5	9.4
6	42.0	24.4	76.6	48.5	36.0	49.2	58.7	8.2	23.7	11.2
7	19.2	34.3	47.8	32.5	28.7	26.2	33.3	20.9	22.5	58.0
8	16.5	5.7	57.0	60.0	26.3	24.1	48.6	0.2	50.5	4.0
9	47.8	10.8	43.1	24.0	25.9	40.0	48.2	11.9	14.7	40.5
10	24.2	61.4	16.6	34.0	31.8	23.2	30.2	25.0	24.5	23.0
11	31.5	1.2	42.0	37.0	32.0	36.0	80.0	11.0	30.3	46.0
12	33.0	64.0	21.0	54.7	48.0	15.5	75.0	7.3	66.0	67.0
13	15.0	30.0	9.0	16.0	21.0	3.0	20.0	18.0	14.0	51.0
14	34.0	52.0	10.5	18.3	22.0	35.0	27.5	14.2	16.3	48.7
15	75.0	13.0	69.0	49.0	21.8	69.5	49.5	7.7	23.0	49.0
16	19.6	65.5	26.5	86.1	17.4	32.6	70.9	42.3	49.6	27.3
17	35.0	35.0	30.0	19.0	0.0	22.0	85.0	62.0	65.0	33.0
18	45.0	0.0	0.0	30.0	45.0	50.0	0.0	0.0	16.5	10.0
19	11.5	58.4	63.3	26.4	26.6	61.1	74.2	28.5	29.8	32.4
20	10.0	95.8	4.0	42.4	40.0	5.9	119.3	60.8	120.3	45.1
21	6.3	24.0	39.5	24.5	33.5	48.8	9.0	79.0	56.3	30.0
22	27.2	26.5	14.0	13.5	6.5	7.5	17.0	9.0	51.3	21.5
>0 mm	22	21	21	22	21	22	21	20	22	22
>40 mm	6	9	10	10	3	7	13	5	7	10
>95th p.v	5	9	11	8	1	9	13	5	7	9
Max.	90.0	95.8	86.4	86.1	54.0	69.5	119.3	79.0	120.3	67.0

Station codes:
1 = Alcantarilla, 2 = Alhama de Murcia, 3 = Embalse de Cierva, 4 = Fuente Alamo, 5 = Lorca, 6 = Totana, 7 = Abanilla, 8 = Aguilas, 9 = Cehegin, 10 = Cieza, 11 = Cuadros, 12 = El Algar, 13 = Elche, 14 = Embalse de Alfonso, 15 = Espuna de Alquerias, 16 = Guadalupe, 17 = Guadamar Seguro, 18 = Moratalla, 19 = Orihuela, 20 = San Javier, 21 = San Miguel Salinas, 22 = Torrevieja.

Table 7.4: Observed daily rainfall (mm) at 11 Agri stations for the extreme winter events shown in Figures 7.7 and 7.8. The table contains some missing values (-). The number of stations at which rainfall is greater than 0 mm and 40 mm is shown at the bottom of the table, together with the maximum recorded value for each day.

Station	25/11/59	19/1/72	3/12/73	4/12/84	5/12/84	29/12/84	30/12/84
	S	HYC	HYC	SE	SE	SE	SE
1	101.0	114.5	19.4	38.0	43.0	-	-
2	57.4	90.0	23.4	-	-	-	-
3	40.0	110.0	140.0	36.0	54.3	66.4	50.4
4	60.2	65.8	-	-	-	-	-
5	202.0	92.4	69.2	39.6	12.4	67.0	49.6
6	314.6	84.2	51.3	34.2	39.5	91.7	64.2
7	62.2	100.0	96.0	20.0	42.0	50.0	28.0
8	113.4	88.1	63.2	16.4	33.0	53.4	3.8
9	60.0	94.0	50.0	25.0	33.0	37.0	30.0
10	0.0	305.0	110.0	-	-	-	-
11	162.4	234.8	42.0	30.1	22.1	112.1	62.1
> 0 mm	10	11	10	8	8	7	7
> 40 mm	9	11	8	0	3	6	4
Maximum	314.6	305.0	140.0	39.6	54.3	112.1	64.2

Station codes:
1 = Aliano, 2 = Corleto Perticara, 3 = Missanello, 4 = Moliterno, 5 = Nova Siri Scalo, 6 = Pisticci, 7 = Roccanova, 8 = Senise, 9 = San Martino d'Agri, 10 = Stigliano, 11 = Tursi.

Table 7.5: Observed daily rainfall (mm) at 22 Guadalentin stations for the extreme summer events shown in Figures 7.11 and 7.12. The number of stations at which rainfall is greater than 0 mm, 40 mm and the 95th percentile value is shown at the bottom of the table, together with the maximum (max.) recorded value for each day.

	4/6/73	25/7/86	19/8/74	22/8/81	18/6/67	10/6/69	15/7/74	4/6/67
Station	C	C	HYC	HYC	UC	UA	UA	E
1	7.0	0.0	66.8	21.8	15.4	22.0	42.0	36.0
2	0.0	0.0	32.0	53.0	5.0	26.0	43.0	16.0
3	51.2	0.0	74.0	45.0	4.1	12.7	13.4	17.7
4	36.0	0.0	83.0	10.0	21.3	0.0	42.0	0.0
5	3.5	1.6	27.5	0.0	18.0	9.8	27.2	21.8
6	6.6	0.0	45.6	0.0	20.0	2.6	68.6	23.0
7	29.7	0.0	23.0	49.0	9.9	4.3	36.0	0.0
8	0.0	26.2	12.3	0.8	52.0	0.0	8.4	0.0
9	2.5	0.0	51.3	0.0	12.1	14.0	20.8	78.8
10	34.2	0.8	47.3	5.1	6.5	15.2	4.1	0.5
11	7.0	1.5	49.0	30.0	3.0	10.0	95.0	23.3
12	13.0	0.0	0.0	81.0	0.0	0.0	22.5	0.0
13	37.5	2.0	24.0	0.0	64.0	54.0	5.5	6.5
14	7.0	0.0	31.5	0.0	8.0	32.0	7.0	19.0
15	0.0	1.2	21.0	29.0	18.0	38.0	6.0	35.0
16	7.6	0.2	36.2	10.7	12.4	40.0	0.0	42.6
17	3.0	1.0	7.0	0.0	31.0	3.0	5.0	25.0
18	4.2	69.5	25.6	0.0	30.0	25.0	25.2	15.0
19	9.9	0.0	23.6	12.3	17.5	49.5	6.2	30.8
20	37.6	0.4	3.0	8.0	15.4	0.0	13.7	70.0
21	5.4	0.0	25.3	0.7	11.1	7.7	12.4	45.0
22	0.0	0.0	7.1	0.0	7.3	5.0	3.1	1.2
>0 mm	18	10	21	14	21	18	21	18
>40 mm	1	1	7	4	2	2	5	4
>95th p.v	5	2	10	4	3	5	5	6
Max.	51.2	69.5	83.0	81.0	64.0	54.0	95.0	78.8

Station codes:
1 = Alcantarilla, 2 = Alhama de Murcia, 3 = Embalse de Cierva, 4 = Fuente Alamo, 5 = Lorca, 6 = Totana, 7 = Abanilla, 8 = Aguilas, 9 = Cehegin, 10 = Cieza, 11 = Cuadros, 12 = El Algar, 13 = Elche, 14 = Embalse de Alfonso, 15 = Espuna de Alquerias, 16 = Guadalupe, 17 = Guadamar Seguro, 18 = Moratalla, 19 = Orihuela, 20 = San Javier, 21 = San Miguel Salinas, 22 = Torrevieja.

Table 7.6: Inter-station correlations for rainfall amount for six stations in the Guadalentin calculated using each station as a baseline in turn, i.e. correlations were calculated using all observed days with rainfall at the baseline station.

Station no. Baseline	1	2	3	4	5	6
1. Alcantarilla	-	0.43	0.41	0.40	0.43	0.42
2. Alhama de Murcia	0.35	-	0.49	0.45	0.48	0.53
3. Embalse de Cierva	0.28	0.47	-	0.42	0.41	0.50
4. Fuente Alamo	0.35	0.46	0.42	-	0.42	0.57
5. Lorca	0.36	0.48	0.42	0.41	-	0.50
6. Totana	0.29	0.48	0.41	0.50	0.43	-

Table 7.7: Inter-station correlations for rainfall amount for eleven stations in the Agri calculated using each station as a baseline in turn, i.e. correlations were calculated using all observed days with rainfall at the baseline station.

Station no. Baseline	1	2	3	4	5	6	7	8	9	10	11
1. Aliano	-	0.52	0.59	0.35	0.43	0.46	0.57	0.52	0.47	0.56	0.48
2. Corleto Perticara	0.61	-	0.63	0.62	0.45	0.46	0.61	0.60	0.68	0.62	0.51
3. Missanello	0.60	0.52	-	0.42	0.41	0.45	0.61	0.54	0.53	0.52	0.46
4. Moliterno	0.51	0.64	0.53	-	0.34	0.35	0.53	0.55	0.67	0.45	0.41
5. Nova Siri Scalo	0.47	0.39	0.45	0.30	-	0.55	0.46	0.49	0.39	0.50	0.59
6. Pisticci	0.50	0.43	0.48	0.30	0.55	-	0.50	0.49	0.42	0.56	0.59
7. Roccanova	0.59	0.54	0.62	0.44	0.45	0.47	-	0.63	0.56	0.54	0.49
8. Senise	0.60	0.59	0.63	0.49	0.55	0.52	0.68	-	0.60	0.58	0.60
9. S.Martino d’Agri	0.54	0.62	0.58	0.58	0.37	0.39	0.58	0.57	-	0.49	0.42
10. Stigliano	0.58	0.51	0.51	0.29	0.46	0.51	0.51	0.49	0.42	-	0.53
11. Tursi	0.50	0.45	0.48	0.32	0.58	0.54	0.51	0.54	0.41	0.54	-

Table 7.8: Advantages and disadvantages of the circulation-type approach to downscaling developed in Chapters 5 and 6.

Advantages

- It is relatively easy to explore the physical reality of the typing scheme (using pressure composites and the $PROP_{ct}/PROP_{tot}$ and $PREC_{ct}/PREC_{tot}$ ratios).
- The typing scheme can be applied anywhere in mid-latitudes.
- There are no unclassified days in the typing scheme (UC/UA-types are actually days with indeterminate/light flow).
- The method is not computationally intensive.
- The approach incorporates regional and large-scale forcing (through the circulation types) as well as more local factors (through the rainfall state of the previous day).
- Conditioning rainfall on circulation type and the rainfall state of the previous day helps to increase temporal persistence and to reduce the ‘overdispersion’ problem.
- The impact of GCM errors can be reduced by using variable thresholds for the circulation types and by selecting the most reliable baseline scenarios.
- Running the weather generator 1000 times (i.e. in true Monte Carlo mode) and presenting the results in the form of frequency histograms has a number of advantages:
    - a range of scenarios can be provided and the level of uncertainty can be indicated, by calculating quantile values, for example;
    - ranked pairs can be used as climate scenarios, thus taking some account of systematic errors in the weather generator and GCM; and,
    - non-ranked pairs can be used in climate sensitivity studies, to maximise the changes in a particular season, for example.
- The full range of results from the weather generator are presented (together with mean values), whereas many other studies only present the mean of 100 (or fewer) iterations of the model.
- It is not necessary to make any decisions about how to perturb the weather generator parameters because the circulation-type sequences are derived objectively from the GCM (although the rainfall occurrence/amount parameters could also be perturbed if desired).
- Circulation-type sequences can also be modelled as a Markov Chain process if very long time series are required.
- The simulated time series of daily rainfall occurrence can be used as a baseline for the simulation of self-consistent time series of rainfall at other sites or of other parameters (such as temperature and radiation).

Disadvantages

- The choice of threshold values in the typing scheme is subjective.
- The method requires a lot of partitioning of the data and the estimation of a fairly large number of parameters: this gives sample size problems and there is a potential danger of overfitting the models.
- The gamma distribution does not always provide an adequate description of daily rainfall amount.
- Initially, downscaled scenarios are only produced for a single site/variable.
- The weather generator output still suffers from the ‘overdispersion’ problem.
- Convective rainfall events are not dealt with in a physically realistic way.
- Circulation is not the only forcing factor for rainfall.
- Analysis and interpretation of the results is time consuming.