2. THE AUTOMATED CIRCULATION-TYPING SCHEME

2.1 DESCRIPTION OF THE UNDERLYING DATA SETS

2.1.1 Observed pressure data

The automated circulation-typing scheme used in the thesis requires daily time series of gridded mean sea level pressure (MSLP) (Section 2.2). One possible source of such data available at the start of the thesis study period was the 5° latitude by 10° longitude data set which covers most of the Northern Hemisphere, referred to as the UK Meteorological Office (UKMO) data set (Jones, 1987). This data set extends back to 1881, is updated, and is held in the Climatic Research Unit. It was, however, decided to use MSLP data from the National Meteorological Center (NMC) CD-ROM data set. This data series is shorter than the UKMO series, extending back to 1946. This is not, however, considered a disadvantage because daily precipitation time series for the main study region (the Guadalentin Basin, southeast Spain) are only available from the late-1950s onwards (Section 3.1). The NMC data are based on twice daily (00 and 12 UTC) operational analyses and are stored on an equally-spaced octagonal grid (47 x 51 points) on a polar stereographic projection with a horizontal resolution of about 380 km (Jenne, 1975). This is higher than the resolution of the UKMO data set and is comparable with that of the current generation of General Circulation Models (about 300 km, see Section 1.1). Another advantage of the NMC CD-ROM data set is that it includes additional free atmosphere variables such as 500 hPa geopotential height which may also be of use in downscaling (Palutikof *et al.*, 1997; Winkler *et al.*, 1997; see also Chapter 7). NMC gridded data for 12 UTC have been used throughout the thesis work, wherever observed pressure data are required. While a number of advantages in using this particular data set can be identified, it should be noted that the various gridded MSLP data sets which are available (such as the recently available National Center for Environmental Prediction (NCEP) Reanalysis data set (Kalnay *et al.*, 1996)) inevitably share a large proportion of common station data.

For the purposes of the preliminary thesis work described in this chapter, MSLP data from the NMC CD-ROM were interpolated to a 2.5° latitude by 3.75° longitude grid for a European window (20° N to 80° N, 50° W to 30° E) using a 16-point Bessel interpolation scheme (based on that provided with the NMC CD-ROM and modified in the Climatic Research Unit). The grid spacing is then the same as that used in the UK Meteorological Office high-resolution transient General Circulation Model experiment (see Section 2.1.2). The NMC data start in 1946, although some of the early years are missing, and end in June 1989. Thus, MSLP data for the period January 1956 to June

1989 were used. Data for the years (1961-1964 and 1977) in which there are concerns about homogeneity (Trenberth and Paolino, 1980; Trenberth and Olson, 1988) were excluded. Major changes in the NMC numerical models were introduced in 1980, 1982, 1986 and 1987 (Trenberth and Olson, 1988) and could have affected homogeneity. However, Palutikof *et al.* (1997) compared the data for two selected decades, 1965-1974 and 1975-1984 (the validation and calibration periods in their study), and did not find any statistical differences between these two periods, nor evidence of discontinuities in the daily means for the more recent decade, 1975-1984.

Mean seasonal SLP data for the period 1956-1989 for the European window calculated from the interpolated data are plotted in Figure 2.1.

2.1.2 UKTR GCM pressure data

The General Circulation Model (GCM) used in the analyses described in Chapters 2-4 is the UK Meteorological Office high resolution GCM run in transient mode, referred to as UKTR (Murphy, 1995a,b; Murphy and Mitchell, 1995). This experiment was used because it represented the modelling state-of-the-art at the time when work commenced and because appropriate daily output was readily available from the Climate Impacts LINK Project based in the Climatic Research Unit (http://www.cru.uea.ac.uk/link/). Daily output was obtained from Years 66-75 of the 75-year long control simulation and from the same years of the perturbed simulation. The grid spacing is 2.5° latitude by 3.75° longitude, as shown in Figure 2.2. The atmospheric model has 11 vertical layers and is coupled with a 17-layer ocean model. The model structure and control-run performance, including the need for large flux adjustments to prevent the occurrence of unacceptable climate drift, are described in detail elsewhere (Murphy, 1995a).

In the perturbed simulation, CO_2 forcing is increased by 1% per annum compound and doubles in Year 70. Averaged over Years 66-75 (the decade spanning the time of CO_2 doubling) the mean global warming, with respect to Years 66-75 in the control simulation, is 1.7° C. This is at the lower end of the climate sensitivity range of 1.5-4.5° C adopted by the Intergovernmental Panel on Climate Change (Houghton *et al*., 1990; 1992; 1996). The spatial and temporal structure of the simulated response to the prescribed CO_2 forcing has been investigated (Murphy and Mitchell, 1995), and the global-mean response evaluated using a simple energy balance model and an oceanic box diffusion model (Murphy, 1995b).

2.2 THE TYPING-SCHEME METHODOLOGY

2.2.1 Introduction

The circulation-typing scheme methodology used here is based on numerical values of flow and vorticity calculated from gridded SLP data (Jenkinson and Collison, 1977) and on the Lamb Weather Type (LWT) classification developed for the British Isles (Lamb, 1972; Jones *et al.*, 1993). The Jenkinson and Collison methodology provides a means of calculating daily values of surface flow and vorticity over a grid in geostrophic units, hPa per 10° latitude at 55° N (the latitude of the central grid point in the original analysis). The flow and vorticity parameters provide information about the direction and type (cyclonic/anticylonic, light/hybrid) of surface flow and can, therefore, be used to reproduce a circulation classification scheme such as the LWT catalogue (Hulme *et al*, 1993; Jones *et al.*, 1993). Provided that the geostrophic units are adjusted to reflect the latitude and the resolution of the gridded data, the Jenkinson and Collison methodology can be applied in any mid-latitude location. One of the major aims of the work described here is to investigate whether this existing automated typing scheme can be successfully applied in a very different climate regime to that of the UK, i.e. in a Mediterranean climate regime.

2.2.2 Calculation of the flow and vorticity parameters

The automated LWT classification scheme (Jenkinson and Collison, 1977; Jones *et al.*, 1993) was originally developed using a 16-point grid centred on 55° N with a resolution of 5° latitude by 10° longitude, reflecting the resolution of the underlying UK Meteorological Office pressure data (Jones, 1987). Here, the higher-resolution gridded SLP data set from the NMC-CDROM is used, interpolated to a 2.5° latitude by 3.75° longitude grid over a European window (see Section 2.1.1). A 32-point grid within this window, centred on 41.25° N and covering the area 36.25° N to 46.25° N and 16.88° W to 9.38° E (Figure 2.2) was used to apply the classification scheme in the Guadalentin Basin.

The first step in the classification procedure was to calculate the following flow and vorticity parameters for the grid shown in Figure 2.2:

- westerly flow (*w*): the westerly component of geostrophic surface wind calculated from the pressure gradient between 38.75° N and 43.75° N;
- southerly flow (*s*): the southerly component of geostrophic surface wind calculated from the pressure gradient between 9.375° W and 1.875° E;

- resultant flow (F): total resultant westerly and southerly flow;
- direction (dir): in degrees (0 to 360°) of the resultant surface wind obtained from w and s, the directional category is calculated on a eight-point compass with a resolution of 45° (e.g. E occurs between 67.5° and 112.5°);
- westerly shear vorticity (zw): difference of the westerly flow between 36.25° N and 41.25° N minus that between 41.25° N and 46.25° N;
- southerly shear vorticity (zs): difference of the southerly flow between 41.25° N and 9.375° E minus that between 41.25° N and 16.875° W; and,
- total shear vorticity (Z): the sum of westerly and southerly flow.

The seven parameters listed above were calculated from the grid-point values using the following equations (adapted from Jenkinson and Collison, 1977; Jones *et al.*, 1993):

$$w = 0.25(23 + 24 + 25 + 26) - 0.25(7 + 8 + 9 + 10) \qquad \text{Equation 2.1}$$

$$s = 1.33[0.125(10+(2\text{x}18)+26+9+(2\text{x}17)+25) - 0.125(7+(2\text{x}15)+23+8+(2\text{x}16)+24)] \qquad \text{Equation 2.2}$$

$$F = (s^2 + w^2)^{1/2} \qquad \text{Equation 2.3}$$

$$dir = \tan^{-1}(w/s) \ \ (+180° \text{ if } w>0 \text{ or } s>0) \qquad \text{Equation 2.4}$$

$$zw = 1.05[0.25(29+30+31+32)-0.25(15+16+17+18)] - 0.95[0.25(15+16+17+18)-0.25(1+2+3+4)] \qquad \text{Equation 2.5}$$

$$zs = 0.66[0.125(12+(2\text{x}20)+28+11+(2\text{x}19)+27) - 0.125(10+(2\text{x}18)+26+9+(2\text{x}17)+25)] - 0.66[0.125(8+(2\text{x}16)+24+7+(2\text{x}15)+23) - 0.125(6+(2\text{x}14)+22+5+(2\text{x}13)+21)] \qquad \text{Equation 2.6}$$

$$Z = zw + zs \qquad \text{Equation 2.7}$$

where the numbers *1-32* refer to the grid-points shown in Figure 2.2. The constants (1.33, 1.05, 0.95 and 0.66) reflect the relative differences between the grid-point spacing in the east-west and north-south direction used here and were calculated following the method of Dessouky and Jenkinson (1975). The multipliers (0.25 and 0.125) reflect the number of grid points used here (twice as many as used by Jenkinson and Collison (1977)). The geostrophic flow and vorticity units are expressed as hPa per 10° latitude at the central latitude (41.25° N).

2.2.3 The fourteen basic circulation types

Lamb (1972) defined seven basic circulation types for the British Isles: anticyclonic, cyclonic, northerly, easterly, southerly, westerly and north-westerly. An eighth circulation type, unclassified, was introduced in the automated classification scheme (Jones *et al.*, 1993). Jones *et al.* followed Lamb's accounting procedure to calculate seasonal and monthly totals, where a hybrid type (such as anticylonic-southwesterly) counts equally to each of its two or three major types. This procedure is not used here because each day must be ascribed uniquely to one particular type. Instead hybrid types are treated as separate types, categorised according to whether flow is anticyclonic or cyclonic, rather than according to the direction of flow (which would have given eight rather than two additional types). Similarly, unclassified or light-flow days are categorised according to whether flow is anticyclonic or cyclonic (giving two additional types). Eight directional types (with a resolution of 45°) are recognised, together with the two "strong" flow types, anticyclonic and cyclonic. Thus a total of fourteen basic circulation types are used here.

The second stage of the classification procedure is to allocate each day to one of these fourteen basic circulation types using the calculated values of the resultant flow (F), total shear vorticity (Z) and direction (*dir*) (see Section 2.2.2) and the definitions shown in Table 2.1.

The F and Z threshold values used to define the unclassified or indeterminate/light-flow circulation types (UC and UA) and the hybrid circulation types (HYC and HYA) were initially chosen to define LWTs in the British Isles (Jenkinson and Collison, 1977; Jones *et al.*, 1993) and may not be the most appropriate for use in other regions. Values of F and Z calculated from observed SLP over the Iberian Peninsula are shown in Figure 2.3. These scatterplots do not show any clustering or grouping, indicating that in this region, as elsewhere (Conway *et al.*, 1996), the threshold values represent arbitrary values imposed on a smooth distribution. The identification of a more appropriate cut-off point within this smooth distribution is not straightforward and hence a value of 6 was retained.

The mean annual and seasonal frequencies of the fourteen basic circulation types calculated from the observed SLP data for the period 1956-1989 are given in Table 2.2. Over the year as a whole, the most frequent circulation types are the two unclassified types (UC and UA). The least frequent types are the SE and S directional types, occurring on average on fewer than five and eight days a year respectively.

2.2.4 The eight circulation-type groups

Some of the fourteen circulation types are relatively infrequent over the study area in at least some seasons (Table 2.2). This makes it difficult to establish reliable statistics for the precipitation regime associated with each type, particularly given the low number of rain days in the Guadalentin Basin (Section 3.1). For this reason, the fourteen basic types were regrouped into eight types, including three directional groups (Table 2.3).

These groupings were made after a preliminary examination of the rainfall data and SLP maps for some randomly-selected days. It is only legitimate to combine types which share precipitation regimes and underlying surface pressure patterns (Huth, 1996). The W, NW, SW and N directional types can be combined because their associated air-masses must all cross the Iberian Peninsula before reaching the Guadalentin and they are not therefore major rain-producers in this region (Romero *et al.*, 1998; Serrano *et al.*, 1999). It would, however, be inappropriate to combine these types if the study area were located on the western or northern Spanish coast where much of the rainfall is associated with Atlantic weather systems (Linés Escardó, 1970; Serrano *et al.*, 1999). The A and HYA-types can be combined because they must both by definition be characterised by high-pressure conditions and they were immediately identifiable as low-rainfall types. It was decided not to combine the C and HYC-types at this stage because of uncertainty over the direction of flow associated with each.

2.2.5 Frequencies of the observed circulation types

The mean annual and seasonal frequencies of the eight circulation-type groups calculated from observed SLP data for the period 1956-1989 are given in Table 2.4. The mean seasonal cycles are shown in Figure 2.4. Mean frequencies simulated by the UKTR GCM are also shown and are discussed in Section 2.4.2.

Over the year as a whole, the most frequently observed circulation types are the two unclassified or indeterminate/light-flow types (UC and UA). The UC-type has a very strong seasonal cycle, with a winter minimum and a summer maximum. The UA-type is most frequent in autumn, but does not have a strong seasonal cycle. In contrast, the A/HYA-group has a very strong seasonal cycle, with a pronounced winter maximum. The C and HYC-types have a late spring/summer maximum and a less pronounced seasonal cycle. The group of westerly and northerly-types (the W/NW/SW/N-group) has a strong seasonal cycle which peaks in late autumn/winter. The E/NE-group is one of the least frequent types and does not have a seasonal cycle.

The least frequent category is the S/SE-group, which is particularly infrequent from May to September.

2.3 VALIDATION OF THE TYPING SCHEME FOR SOUTHEAST SPAIN

2.3.1 Construction of SLP composites from the observations

For the typing scheme to be valid for southeast Spain, each of the eight circulation-type groups should have a characteristic underlying synoptic pattern, which is physically distinct and produces the expected type and direction of surface flow (Huth, 1996). To test this, composite SLP maps were constructed showing the mean pattern and the anomaly pattern, for each circulation type and each season, from the NMC CD-ROM data. Mean pressure and anomaly maps for each season are shown in Figures 2.5 and 2.6 respectively.

The anomaly maps (Figure 2.6) were constructed by subtracting the long-term day mean from the mean of all days of a particular type. For example, to calculate the anomaly for the E/NE-type in winter, the SLP pattern for all days in December, January and February for the period 1956-1989 classified as E/NE was calculated. The long-term day mean was calculated as the mean of all other days with the same date.

Anomaly grid-point values which are significant at the 5% level were identified using the *t* test and the field significance was also calculated. All the anomaly patterns were found to be significant at the 5% level. For the sake of clarity, therefore, individual significant grid points are not indicated in the figures. In order to provide a common baseline for the composites, mean seasonal SLP maps were also produced from the NMC data set (Figure 2.1).

2.3.2 Interpretation of the SLP composites

All the mean and anomaly patterns produce the expected type and direction of flow over southeast Spain (Figures 2.5 and 2.6). Most are consistent from season to season, although the magnitude of the anomalies and the detail of the patterns show some variability. Larger anomalies occur in winter and autumn than in summer, for example.

The composites cover a wider geographical area than the 32-point grid used in the classification scheme. They can, therefore, also be used to investigate relationships between flow over the study area and large-scale features of the circulation such as the Azores and Siberian anticyclones, which exert a strong influence on variations of pressure over the Mediterranean area (Bartzokas, 1989).

The cyclonic-types (C and HYC) are characterised by a weaker Icelandic Low, a less extensive Azores High, tilted to the northeast, and a low-pressure anomaly centred over the Iberian Peninsula (Figures 2.5 and 2.6). The A/HYA-group is associated with a stronger and more extensive Azores High, and with a deeper Icelandic Low. The cyclonic and anticyclonic patterns are reverse images of each other, and appear to represent different phases of the North Atlantic Oscillation (NAO). The cyclonic pattern is very similar to the Greenland Above mode of the NAO, while the anticyclonic pattern resembles the Greenland Below mode (Van Loon and Rogers, 1978). These relationships are the opposite to those expected for the UK, where the Greenland Below mode of the NAO is associated with stronger westerly flow and more disturbed weather conditions. They are, however, supported by the negative correlations found between winter precipitation and the NAO index in southern Europe, in contrast to the positive correlations found for northern Europe and parts of Scandinavia (Hurrell, 1995; and see discussion in Section 3.3).

The HYC-type anomaly patterns are very similar to the C-type patterns, although the HYC-type anomalies are somewhat smaller in magnitude (Figure 2.6). The similarity of these patterns suggests that it may be legitimate to combine the two types. However, this cannot be done without first demonstrating that they also share a similar rainfall regime (see Section 3.2). The UC-type anomalies are considerably smaller in magnitude than both the C and HYC-type anomalies in every season, and occasionally positive rather than negative (Figure 2.6). The pattern of these anomalies is also different, particularly in winter and summer. Similarly, the anomalies associated with the UA-type are considerably smaller in magnitude than those associated with the A/HYA type group (Figure 2.6).

In the case of the W/NW/SW/N-group, a low pressure anomaly is located over southern UK/northwestern France (Figure 2.6), suggesting that the North Atlantic storm tracks are shifted south of their normal position. The Azores High maintains its normal position (Figure 2.5).

With E/NE-type flow, a high-pressure centre appears to the northwest of France/southeast of Ireland (Figure 2.5). Another characteristic feature of this circulation type is a small area of negative anomalies centred over the southern/central Mediterranean Sea (Figure 2.6). These anomalies may be related to intensification of action in the areas of cyclogenesis in the Gulf of Genoa and Northwest Africa, and possibly the area of Alpine lee cyclogenesis in the Gulf of Lions (Linés Escardó, 1970; Dalu and Gregorio, 1987; Alpert *et al.*, 1990; Prezerakos *et al.*, 1990). The contours indicating the boundary between the low-pressure anomaly and the more extensive, high-pressure anomaly to the north lie across southeast Spain, channelling flow along the coast.

Except in summer, S/SE-type flow is associated with higher pressure throughout central and northwest Europe, and with an area of lower pressure to the southwest of the Iberian Peninsula (Figure 2.6). The Azores High is almost unrecognisable as a high pressure feature (Figure 2.5). It is possible that the high pressure over central and northwest Europe is related to the westward extension of the Siberian anticyclone. The contours indicating the boundary between the high-pressure and low-pressure anomalies lie just to the east of the Guadalentin Basin (Figure 2.6), giving strong southerly/southeasterly flow over the region. The anomaly pattern is somewhat different in summer with a strengthening of the Azores High, although this type only occurs, on average, once each summer.

On the basis of the SLP composite maps, it was concluded that each of the eight circulation-type groups has a characteristic underlying pressure pattern, which is physically distinct and produces the expected type and direction of surface flow over southeast Spain and the Guadalentin Basin. (It is noted, however, that the C and HYC-types have similar underlying pressure patterns and that it may be legitimate to combine them.) It is therefore valid to apply this classification scheme in southeast Spain. It provides an appropriate basis for the next stage in the development of the downscaling methodology, the identification of relationships between the circulation types and daily rainfall (see Section 3.2). First, however, the ability of the UKTR GCM to reproduce the observed circulation types is investigated.

2.4 VALIDATION OF UKTR GCM CIRCULATION TYPES

2.4.1 Sea-level pressure patterns

Inspection of MSLP fields from the UKTR control run for winter and summer indicates that the model is reasonably successful in reproducing the main features of the general circulation system although some systematic errors can be identified (Figure 25 from Murphy, 1995a). In winter, for example, the Siberian anticyclone is too weak, and the Icelandic Low extends too far eastwards into central Europe. For the validation studies reported here, mean seasonal SLP maps were constructed for the Northeast Atlantic and Europe from UKTR control-run daily data, as shown in Figure 2.7. Control-run minus observed differences are also shown and indicate that the simulated Icelandic Low is too intense in every season. The position and intensity of the Azores

High is well simulated in winter and spring. In summer it does not extend far enough eastwards and in autumn it extends too far eastwards.

A more detailed study of UKTR storm tracks and cyclones during winter confirms that there are "substantial errors in the position of the mid-latitude storm tracks" particularly in the eastern North Atlantic (Carnell *et al.*, 1996). Atlantic storm tracks extend too far into Europe and too far south, reaching a maximum over Mediterranean latitudes. The model tends to over-predict the frequency of weak Atlantic depressions and to under-predict the frequency of very deep depressions (Carnell *et al.*, 1996).

These studies (Murphy, 1995a; Carnell *et al.*, 1996) indicate that, like other GCMs of the same generation (Liang *et al.*, 1996; Risbey and Stone, 1996) and earlier versions of the UK Meteorological Office model (Huth, 1997), the UKTR model is able to reproduce the main features of the large-scale general circulation but fails to reproduce its finer details. However, a validation study more appropriate for the purposes of this study is provided by determining how well the model simulates the circulation types over the Iberian Peninsula.

2.4.2 Simulated circulation-type frequencies

Seasonal and monthly frequencies of the eight circulation-type groups were calculated from the ten years of control-run output of the UKTR model. These are compared with the observations in Figure 2.4. The minimum and maximum observed frequencies in any decade during the period 1956-1989 are indicated by the hatched area. Whenever the UKTR values fall within this area the model is considered to be performing well. Thus the model reproduces the seasonal cycles of the HYC, UC and S/SE-types reasonably well.

The differences (in number of days and standard deviation units) between the mean seasonal circulation-type frequencies calculated from model output and from the observations (all 30 years, 1956-1989) are given in Table 2.5. Significant differences are identified using the Mann Whitney/Wilcoxon rank sum test (a non-parametric equivalent of the *t* test).

Fifty per cent of all differences are significant. Some of the errors are quite large, greater than one standard deviation unit in nearly 40% of cases, and greater than two standard deviation units in 10% of cases. More significant errors occur in winter and summer than in spring and autumn.

The UC-type is underestimated in every season (significantly so in every season except autumn), and the A/HYA-type overestimated in every season (significantly so in every season except winter). However, most of the differences between the simulated and observed frequencies are not consistent from season-to-season. The model underestimates the frequency of the C and HYC types in spring and summer, and over the year as a whole. These circulation types, together with the UC-type, are all associated with a weaker than normal Icelandic Low (Figure 2.6) so this error is probably related to the overestimation of the intensity of the Icelandic Low (Figure 2.7). The frequency of the E/NE-type is underestimated by the model in every season except summer, when it is overestimated. This gives a more intense seasonal cycle than seen in the observations. This same feature is seen for the frequency of the UA-type which is significantly underestimated in winter and significantly overestimated in summer. The frequency of the S/SE-types is simulated fairly well, except in winter (underestimated) and autumn (overestimated). The W/NW/SW/N-group is overestimated in winter and spring, and over the year as a whole, but underestimated in autumn. Only the winter and autumn differences are significant.

The errors identified here suggest that there may also be problems with the day-to-day sequence and persistence of the simulated circulation types. However, it was considered that the performance of the UKTR model was adequate for the major purpose of the analyses reported in Chapters 2 and 3, which was to evaluate the potential of the circulation-type based approach for regional scenario construction and to provide some illustrative results.

2.4.3 Simulated relationships between the circulation types and synoptic features

A further validation test is provided by comparing SLP composite maps for each circulation-type group constructed from UKTR control-run model output with maps constructed from observed data (Figure 2.6). The pressure patterns over the 32 grid points used to define each type (Figure 2.2) must be similar because the same classification system is used for observed and model data. However, the composites cover a wider geographical area, and the subject of interest is the ability of the model to reproduce the variations in large-scale circulation with circulation type which were identified in Section 2.3.2. Comparisons were made for each season; anomaly maps for the UKTR model are shown in Figure 2.8.

The position and sign of the anomalies are very similar in the observed (Figure 2.6) and simulated (Figure 2.8) composites. However, the simulated anomalies tend to be smaller in magnitude than the observed. This is most evident in the case of the negative anomalies associated with the W/NW/SW/N-type in winter. The magnitudes of the positive anomalies associated with the E/NE-type are underestimated in every season except winter. The tendency to underestimate the strength of the anomalies may arise because only ten years of model data are available, but is most likely to be related to low year-to-year variability in the model.

2.5 FUTURE CHANGES IN CIRCULATION-TYPE FREQUENCY

2.5.1 Mean sea level pressure changes

The mean winter and summer SLP fields simulated by the UKTR GCM show some coherent changes over the North Atlantic/Europe region from the control to the perturbed simulation (Figure 24 from Murphy and Mitchell, 1995). In winter, the strength of Atlantic storm tracks (Carnell *et al.*, 1996), and the temperature gradient between 30 and 60° N (Murphy and Mitchell, 1995), increase in the perturbed simulation. Enhanced westerly flow is simulated across northwest Europe in winter and the frequency of deep depressions increases (Carnell *et al.*, 1996). These changes are related to a reduction in SLP over the Arctic Ocean and over the mid-latitude continents, and to an increase over the mid-latitude oceans. The SLP changes are similar in winter and summer. Summer changes, although smaller in magnitude, have a greater statistical significance (Murphy and Mitchell, 1995). These patterns of change are apparent after the first few decades of the experiment, but, even by the final decade, their amplitude is “small when compared with unforced interannual variations” (Murphy and Mitchell, 1995). The storm-track changes are “unlikely to be statistically detectable” (Carnell *et al.*, 1996). Moreover, the “largest changes occur in the region of greatest model systematic error and must therefore be treated with caution” (Carnell *et al.*, 1996).

The change (perturbed-run minus control-run) in mean seasonal SLP for the study area is shown in Figure 2.9. The winter map shows the increase in westerly flow across northwest Europe indicated by Murphy and Mitchell (1995), with lower pressure to the north and higher pressure over the British Isles, western and central Europe, and the Mediterranean. The SLP increase over the Iberian Peninsula is in the range 1-2 hPa. In every other season, SLP decreases over the Peninsula, by 0-0.5 hPa in spring and by 0.5-1 hPa in summer and autumn. How do these ‘small’ changes in SLP translate into changes in circulation-type frequency?

2.5.2 Seasonal changes in circulation-type frequency

Seasonal and monthly frequencies of the eight circulation-type groups were calculated using SLP data from the UKTR perturbed run. The mean seasonal changes (perturbed-run minus control-run) are shown in Table 2.6. Significant changes (at the 5% and 10% level) are identified using the Mann Whitney/Wilcoxon rank sum test.

The largest changes, and the only ones which are significant at the 5% level, occur in summer. There is a significant increase in the frequency of the C and HYC-types and a significant decrease in the frequency of the A/HYA and UA-types, reflecting the lower SLP over the Iberian Peninsula (Figure 2.9). The frequency of the UC, E/NE and S/SE-types increases in summer, but the changes are not significant. The W/NW/SW/N group shows a non-significant decrease in this season.

The only other significant changes (at the 10% level only) are an increase in the frequency of the S/SE-type in winter, a decrease in the frequency of the E/NE-type in spring and an increase in the W/NW/SW/N-group in autumn. Thus few significant or consistent changes in circulation-type frequency are predicted in seasons other than summer. In spring, however, decreases in the C, HYC, E/NE and S/SE-types are offset by increases in the UA and W/NW/SW/N-types.

SLP composite maps were constructed using perturbed-run model output. The anomaly patterns (Figure 2.10) are very similar to the control-run patterns (Figure 2.8). This similarity suggests that the relatively small changes in MSLP are not associated with changes in the synoptic situation underlying each circulation type but rather with changes in their frequency.

2.6 DISCUSSION

In this chapter it has been demonstrated that the automated LWT classification scheme (Jenkinson and Collison, 1977; Jones *et al.*, 1993) can be successfully transferred to another region, southeast Spain. The fourteen basic circulation types were combined into eight groups to facilitate the analysis. These groups provide a legitimate basis for downscaling because daily MSLP composite maps show that each group has a characteristic pressure pattern which produces the expected type and direction of flow over southeast Spain and the Guadalentin Basin. The next stage in the development of the downscaling methodology was to investigate whether there are consistent and distinct relationships between these circulation-type groups and daily rainfall in the study region (Section 3.2).

The ability of the GCM used here, the UKTR model, to reproduce the observed atmospheric surface circulation has also been investigated. Systematic errors can be identified in the large-scale circulation simulated by the control run (most notably, the Icelandic Low is too intense in every season). Such errors inevitably affect the ability of the model to reproduce the observed circulation types, but the major problems are associated with the frequency of the circulation types rather than with the underlying synoptic pattern. The UC-type, for example is underestimated in every season (significantly so in every season except autumn).

Comparison of perturbed-run and control-run output from the UKTR experiment indicates that the projected changes in MSLP and circulation-type frequency in response to a doubling of the pre-industrial atmospheric CO_2 concentration are generally small, and are not consistent from season to season. Except in summer, the changes in circulation-type frequency at the time of CO_2 doubling are not significant. When using UKTR output to develop the downscaling methodology (Section 3.4) it is, therefore, important to remember that the model errors may be greater than the changes projected for the future. Issues of UKTR model reliability are discussed further in Chapters 3 and 4.

2.7 SUMMARY OF CONCLUSIONS

- In this initial test of the typing methodology in the Guadalentin, it is shown that each of the eight circulation-type groups has a characteristic underlying pressure pattern, which is physically distinct and produces the expected type and direction of surface flow over southeast Spain and the study area.
- Systematic errors can be identified in the ability of the UKTR model to reproduce the observed frequencies of the circulation types. In comparison to the control-run errors, the perturbed minus control run errors in circulation-type frequency are generally small and not consistent from season to season. Except in summer, the changes are not statistically significant.

Table 2.1: The fourteen basic circulation types.

Values of Z and F		*Description*	*Type*
$Z < F$		Directional (resolution of 45°)	N,NE,E,SE, S,SW,W,NW
$Z > 2F$	$Z > 0$	Cyclonic	C
	$Z < 0$	Anticyclonic	A
$Z < 6$ and $F < 6$	$Z > 0$	Unclassified Cyclonic	UC
	$Z < 0$	Unclassified Anticyclonic	UA
$F < Z < 2F$	$Z > 0$	Hybrid Cyclonic	HYC
	$Z < 0$	Hybrid Anticyclonic	HYA

Table 2.2: Mean annual (calendar year) and seasonal frequencies (days) of the fourteen basic circulation types calculated from the observed data, 1956-1989.

Type	*Annual*	*Winter*	*Spring*	*Summer*	*Autumn*
C	19.1	2.0	6.3	8.2	2.8
HYC	19.4	3.2	5.4	7.1	3.4
UC	90.8	5.9	20.9	42.4	21.1
A	20.5	10.7	2.8	1.1	5.9
HYA	21.4	11.1	4.2	0.8	5.1
UA	79.0	17.2	19.6	18.4	25.0
N	26.4	7.7	8.8	3.3	6.6
NE	22.3	6.2	6.5	4.5	5.1
E	11.2	2.1	2.8	3.5	2.8
SE	4.8	1.1	1.7	1.0	1.0
S	7.8	3.0	2.3	0.3	2.2
SW	14.3	6.6	3.4	0.3	4.0
W	12.2	5.5	3.4	0.3	3.0
NW	15.5	7.0	3.9	1.1	3.5

Table 2.3: The eight circulation-type groups.

Type	*Description*
C	Cyclonic
HYC	Hybrid-cyclonic
UC	Unclassified/light flow-cyclonic
A/HYA	Anticyclonic/hybrid-anticyclonic
UA	Unclassified/light flow-anticyclonic
W/NW/SW/N	Westerly/northwesterly/southwesterly/northerly directional types (202.5° - 22.5°)
E/NE	Easterly/northeasterly directional types (22.5° - 112.5°)
S/SE	Southerly/southeasterly directional types (112.5° - 202.5°)

Table 2.4: Mean annual (calendar year) and seasonal frequencies (days) of the eight circulation-type groups calculated from the observed data, 1956-1989.

Type	*Annual*	*Winter*	*Spring*	*Summer*	*Autumn*
C	19.1	2.0	6.3	8.2	2.8
HYC	19.4	3.2	5.4	7.1	3.4
UC	90.8	5.9	20.9	42.4	21.1
A/HYA	41.9	21.8	7.0	1.8	11.0
UA	79.0	17.2	19.6	18.4	25.0
W/NW/SW/N	68.6	26.7	19.5	5.0	16.7
E/NE	33.1	8.3	9.3	7.9	7.8
S/SE	12.3	4.1	4.0	1.2	3.2

Table 2.5: Actual differences (simulated minus observed (days)) and standardized differences (difference / observed standard deviation (σ units)) between observed and simulated circulation-type frequencies. Differences which are significant at the 5% level are indicated (**).

Type	*Annual*	*Winter*	*Spring*	*Summer*	*Autumn*
Days					
C	-6**	+2**	-3	-5**	0
HYC	-1	+1	-1	-1	<1
UC	-28**	-2**	-9**	-15**	-1
A/HYA	+28**	+3	+12**	+8**	+6**
UA	+2	-9**	+2	+6**	+2
W/NW/SW/N	+8	+14**	+4	<1	-10**
E/NE	-5	-6**	-6**	+8**	-1
S/SE	+2	-2**	+1	-1	+4**
σ units					
C	-1.0	+1.3	-0.7	-1.0	0.0
HYC	-0.2	+0.4	-0.3	-0.3	+0.1
UC	-1.8	-0.9	-1.7	-1.7	-0.1
A/HYA	+2.6	+0.4	+3.5	+2.6	+1.3
UA	+0.1	-1.3	+0.3	+0.6	+0.3
W/NW/SW/N	+0.6	+1.8	+0.7	-0.1	-1.4
E/NE	-0.6	-1.2	-2.0	+2.3	-0.4
S/SE	+0.4	-1.0	+0.2	-0.1	+1.3

Table 2.6: Mean seasonal changes (perturbed run minus control run) in the frequency (number of days) of the eight circulation-type groups. Changes which are significant at the 5% (**) or 10% (*) level are indicated.

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	-0.5	-0.7	+4.4**	-0.8
HYC	+0.4	-1.5	+3.1*	-0.4
UC	-0.8	+0.3	+3.6	+2.4
A/HYA	0.0	-0.8	-4.3**	-2.7
UA	+3.5	+2.3	-7.3**	-2.7
W/NW/SW/N	-4.5	+3.1	-1.0	+3.5*
E/NE	-0.2	-1.4*	+1.1	-0.4
S/SE	+2.1*	-1.1	+0.4	+1.2