5. DEVELOPMENT OF A NEW TYPING SCHEME

5.1 THE HADCM2 INTEGRATIONS

The analyses described in Chapters 2-4 use output from the UKTR model (Murphy, 1995a,b; Murphy and Mitchell, 1995). The analyses described in the remaining Chapters use output from a more recent set of GCM simulations performed at the UK Hadley Centre, referred to as HadCM2 (Mitchell *et al*., 1995; Mitchell and Johns, 1997; Johns *et al*., 1997; Tett *et al*., 1997).

Output from three HadCM2 integrations was available for the thesis work:

(i) HadCM2CON: a control run from 1860 to 2100 in which greenhouse gas concentrations are held constant at pre-industrial (taken to be 1750) levels;

(ii) HadCM2GHG: a greenhouse gas only simulation from 1860 to 2100 in which atmospheric CO_2 concentrations are based on historical data up to the present, and then increased at a rate of 1% per annum compound over the period 1990-2099; and,

(iii) HadCM2SUL: atmospheric CO_2 concentrations as HadCM2GHG, plus sulphate aerosols. The direct forcing from sulphate aerosols is represented by increasing the surface albedo in the clear-sky fraction of each grid box. Historical changes in sulphate aerosol are used for the period 1860-1989. The sulphate forcing for 1990-2099 is equivalent to the IPCC IS92a scenario.

Mean annual global temperature time series from the three HadCM2 integrations are shown in Figure 5.1. It was decided to use output from HadCM2SUL for the thesis work because mean global temperature from this integration shows closer agreement, in comparison with output from the other two integrations, with the observed temperature record (Mitchell *et al*., 1995). Daily output for 1956-1989 is used to evaluate model performance (Sections 5.3 and 5.6), while daily output for three decadal time slices [1970-1979 (present-day); 2030-2039 (mid 21st century); and 2090-2099 (late 21st century)] is used to construct climate-change scenarios (Sections 5.7 and Chapter 6).

The HadCM2 model is described in detail by Johns *et al*. (1997). The spatial resolution is the same as UKTR, 2.5° latitude by 3.75° longitude, but it has 96 x 73 grid boxes whereas UKTR has 96 x 72 boxes. This means that the HadCM2 grid is shifted half a box south-eastwards of the UKTR grid (see Section 5.2). HadCM2 has 19 atmospheric levels and 20 ocean levels, compared with 11 and 17 levels respectively in UKTR. The atmospheric component was rewritten for HadCM2: the scheme for atmospheric dynamics, for example, is completely different (Johns *et al*., 1997). There are also major differences in the ocean and sea-ice components of the two models. Improved coupling between the ocean and atmosphere components of HadCM2 means that fewer flux adjustments are required and the control run, HadCM2CON, does not exhibit the 'climate drift' in mean global temperature which occurs in the UKTR control run (Johns *et al*., 1997). Thus there are substantial differences in the underlying UKTR and HadCM2 models as well as differences in the imposed forcing. The main conceptual difference between the two sets of integrations is that the UKTR integrations are transient 'cold-start' simulations, whereas the HadCM2 integrations are transient 'warm-start' simulations incorporating historical forcing.

The sensitivity of HadCM2 to a doubling of atmospheric CO_2 is ~3.0° C. This is in the middle of the climate sensitivity range of 1.5-4.5° C adopted by the IPCC (Houghton *et al*., 1990; 1992; 1996). The sensitivity of HadCM2 is considerably greater than that of UKTR (1.7° C), reflecting the major differences in the parameterisations used in the two models (Johns *et al*., 1997). However, incorporation of the direct effects of sulphates in HadCM2SUL reduces the change in mean annual global temperature simulated at the end of the 21st century by about 1° C in comparison with HadCM2GHG (Figure 5.1).

5.2 THE THREE STUDY REGIONS

5.2.1 A Mediterranean transect

The work described in Chapters 2-4 focuses on the Guadalentin Basin in southeast Spain. Here, two additional study regions are considered (see Figure 1.1). These are the Agri in central Italy and Lesvos in the Aegean Sea, one of the easternmost Greek islands. All three regions are target areas in the Mediterranean Desertification and Land Use (MEDALUS) research project (Brandt and Thornes, 1996; Geeson and Brandt, 2000). They provide a transect across the Mediterranean Basin, with the grids for automatic circulation classification centred on 40° N (Figure 5.2, see Section 5.2.3). The three regions are representative of conditions in the western, central and eastern Mediterranean respectively, although, in terms of rainfall, Italy could also be classified as western Mediterranean (Corte-Real *et al*., 1995b). Provided that sufficient climate data are available, this transect allows the investigation of possible differences across the basin, including the reality of the proposed Mediterranean Oscillation (Corte-Real *et al*., 1995b; Palutikof *et al*., 1996; Reddaway and Bigg, 1996; Piervitali *et al*., 1997).

The rainfall regime of the Guadalentin Basin is discussed in Section 3.1. The subset of six stations used for the construction of scenarios based on UKTR output is also described in Section 3.1. Five of these stations are located in the Guadalentin Basin itself (Alcantarilla, Alhama de Murcia, Fuente Alamo, Lorca and Totana) and are used for the HadCM2-related work described here and in following chapters. The sixth station, Aguilas, located just outside the basin, is replaced by Embalse de Cierva for the HadCM2 work. This new station is located 22 km to the north of Alhama de Murcia (Figure 3.1), at an altitude of 400 m. It has a mean annual rainfall of 266 mm and the mean number of rain days is 31 (both mean values are calculated over the period 1958-1987).

A set of daily precipitation time series for 11 stations in the Agri, obtained through the MEDALUS project, is used for the HadCM2-related work (Table 5.1; Figure 5.3). The period of record available for these stations ranges from 1951-1977 to 1951-1992. The characteristics of the Agri rainfall regime and standardised anomaly indices for this region are discussed in Section 5.2.2. Daily data were not available for Lesvos. Hence analyses for the third study region are restricted to analyses of circulation-type frequency.

5.2.2 The rainfall regime of the Agri basin and comparison with the Guadalentin

The Agri river is located in the Basilicata region of southern Italy and flows into the Gulf of Taranto. The basin is about 200 km in length, extending in width from approximately 90 km at the western end, to about 15 km at the eastern end (Figure 5.4). The altitude of the 11 stations used here (Table 5.1) ranges from 2 m at Nova Siri Scalo on the coast to 879 m at Moliterno, the most westerly station (Figure 5.5). Altitude also increases away from the river channels up to the hill tops forming the northern and southern boundaries of the catchment, from 497 m at Aliano in the centre of the basin to 909 m at Stigliano (the highest of the 11 stations) which is located to the north of Aliano and the Sauro tributary.

Mean annual rainfall at the 11 stations ranges from 550 mm at Nova Siri Scalo to 1134 mm at Moliterno, reflecting the strong east to west gradient in altitude and precipitation along the basin (Table 5.1; Figure 5.6). Similarly, the mean number of rain days at the 11 stations reflects the east/west and north/south gradients in the basin, ranging from a minimum of 83 days at Aliano, which is located close to the river channel in the centre of the basin, to a maximum of 137 days at Moliterno, which is located in the higher western end of the catchment (Figure 5.7).

Thus in the Agri, there is a strong negative relationship between altitude and longitude (Figure 5.5) which is reflected in a strong negative relationship between mean annual rainfall and longitude (Figure 5.6a) and a strong positive relationship between mean annual rainfall and altitude (Figure 5.6b). Weaker relationships occur for the mean number of rain days (Figure 5.7). These relationships can be compared with those for the Guadalentin. With the exception of Alhama de Murcia, altitude tends to decrease from west to east in the Guadalentin (Figure 5.8). Mean annual rainfall also tends to increase weakly from west to east, with Alhama de Murcia (the station with the highest altitude and mean annual rainfall; Table 3.1) as an outlier (Figure 5.9a). The mean number of rain days also tends to increase from west to east (Figure 5.10a). With the exception of Alhama de Murcia, mean annual rainfall appears to be negatively correlated with altitude (Figure 5.9b). In contrast, the mean number of rain days appears to be positively correlated, with Alcantarilla (the station with the greatest number of rain days; Table 3.1) as on outlier (Figure 5.10b). Only six stations are plotted in Figures 5.8 to 5.10, compared with 11 for the Agri (Figures 5.5 to 5.7). The relationships for the Guadalentin are weaker and less systematic than those for the Agri. This may reflect the smaller sample size. However, mean annual rainfall for 22 stations from the area of the Guadalentin Basin (including the six shown in Figures 5.8 to 5.10) is plotted against longitude and latitude in Figure 5.11, and indicates that there are no systematic relationships between location and rainfall in the Guadalentin area. (Altitudes were not available for the additional stations shown in Figure 5.11, hence this relationship could not be tested.)

The mean seasonal cycle of rainfall for the 11 Agri stations is shown in Figure 5.12. It is similar at all stations, peaking in November or December with a pronounced summer minimum. The drier stations, such as Aliano, Pisticci and Tursi, tend to have a weaker, secondary rainfall maximum in May. This secondary peak is, however, considerably weaker than that which occurs in the Guadalentin Basin (Figure 3.3). Even the driest of the Agri stations experience about twice as many rain days as the wettest stations in the Guadalentin Basin, and mean annual precipitation is typically at least two to three times greater in the Agri than in the Guadalentin. The higher frequency of rainfall events in the Agri means that problems relating to small sample size, particularly when partitioning data by season and circulation type, should not be as severe as in the Guadalentin.

Standardised anomaly indices (SAIs) were constructed for the Agri using the method described in Section 3.1.3 and rainfall series for 1951-1992 for eight stations (Aliano, Armento, Calvello, Missanello, Pisticci, Roccanova, San Martino d'Agri and Tursi). The annual and seasonal SAIs are shown in Figure 5.13. Linear trends were calculated for each SAI, but only that for autumn is statistically significant and therefore shown on the Figure. The winter SAI shows a trend towards drier winters from the mid-1970s onwards, following a run of six relatively wet winters centred on 1970. The tendency towards drier winters in recent years is interrupted by one wet winter. This peak reflects the extreme rainfall event of 26 December 1990. The maximum daily rainfall amounts recorded in the series for three stations occurred on this particular day (156, 180 and 112 mm at Aliano, Missanello and Roccanova respectively). Relatively dry years tend to occur more frequently in the second half of the annual SAI, reflecting the trends in the winter and autumn SAIs. The tendency towards decreasing rainfall is stronger in the Agri than in the Guadalentin (the Guadalentin SAIs are discussed in Section 3.1.3).

The contrasts between the earlier and later years of the Agri record are demonstrated by comparing mean rainfall totals for the first decade (1951-1960) with the most recent complete decade (1981-1990) for one representative station, Pisticci. Mean annual rainfall for 1981-1990 is 461 mm, only about 60% of that for 1951-1960 (758 mm). The seasonal values (Figure 5.14) indicate that the largest difference between the two periods occurs in autumn, with somewhat smaller differences in winter and spring, and little difference in summer. A tendency towards lower rainfall over Italy and the central Mediterranean region has been reported in a number of previous studies, although these trends are not always statistically significant (Palmieri *et al*., 1991; Montanari *et al*., 1996; Palutikof *et al*., 1996; Piervitali *et al*., 1997). This trend continued through the first half of the 1990s, although it was stronger in northern Italy than in southern Italy, and 1996 was the wettest year during the period 1960-1996 (Mariani, 1999).

5.2.3 The effects of shifting the pressure grid

For the purposes of the HadCM2-related work described in this and following chapters, MSLP data for the period 1956-1989 from the NMC CD-ROM (see Section 2.1.1 for a description of this data set) were interpolated to the HadCM2 grid for a European window using the 16-point Bessel interpolation scheme used previously. It was necessary to re-interpolate the data because, although the spatial resolution of HadCM2 is the same as UKTR, the number of grid boxes and their position is slightly different. HadCM2 has 73 rows of latitudinal grid boxes, while UKTR has 72. Both models have 96 columns of longitudinal grid boxes, but in HadCM2 the centre, rather than the edge, of the first box is aligned with the 0° meridian. This means that the

HadCM2 grid is shifted half a box south-eastwards (i.e. 1.25° southwards and 1.88° eastwards) of the UKTR grid.

The differences in the two model grids mean that a re-positioned 32-point grid had to be identified in order to re-apply the automated circulation classification scheme (Section 2.2) to the Guadalentin study region. The latitudinal centre of the new grid was taken as 40° N, which also provides an appropriate centre point for the other two study regions. Initially the longitudinal centre of the new Guadalentin grid was taken as 5.63° W, but it was decided to shift the grid eastwards by one grid box giving a central point of 1.88° W. Longitudinal centres of 16.88° E and 28.13° E were selected for the Agri and Lesvos study regions. The three grids are shown in Figure 5.2 and are referred to as HadCM2-$GRID_{1\cdot 88W}$, HadCM2-$GRID_{16\cdot 88E}$ and HadCM2-$GRID_{28\cdot 13E}$ respectively.

Flow and vorticity parameters were calculated for each grid using the method described in Section 2.2.2 and observed (NMC) data for 1956-1989. This is the first step in the circulation classification procedure. Slightly different constants were used in Equations 2.2, 2.5 and 2.6, however, reflecting the differences in the HadCM2 and UKTR grids (values of 1.31, 1.06, 0.95 and 0.64 were used for the HadCM2-grid constants, compared with 1.33, 1.05, 0.95 and 0.66 for the UKTR grid). The same set of constants was used for all three study regions, because the grid-point spacing in the east-west and north-south directions is the same. Thus the geostrophic and vorticity units calculated over all three HadCM2 grids are expressed as hPa per 10° latitude at 40° N.

The second stage of the classification procedure is to allocate each day to one of the 14 basic circulation types using the calculated values of the resultant flow (*F*), total shear vorticity (*Z*) and direction (*dir*) as described in Section 2.2.3 (Table 2.1). The mean seasonal cycle of the frequency of each of these circulation types calculated for HadCM2-$GRID_{1\cdot 88W}$ is shown in Figure 5.15. Two versions of the classification scheme for this grid are shown. In the first version (HadCM2-$GRID_{1\cdot 88W}$-6), *F* and *Z* threshold values of 6 are used to define the unclassified or indeterminate/light flow circulation types (UC and UA) as in the original scheme (Section 2.2.3). In the second version (HadCM2-$GRID_{1\cdot 88W}$-4), threshold values of 4 are tested. The original threshold values were chosen to define Lamb Weather Types in the UK and may not be appropriate for other regions. The study regions used here are located southwards of the major North Atlantic storm tracks, hence westerly flow is weaker than over the UK, and a lower threshold value may be more appropriate. *F* and *Z* values are smoothly distributed (see Figure 2.3 and discussion in Section 2.2.3), hence the choice of both values (6 and 4) is somewhat arbitrary.

Seasonal cycles of circulation-type frequency calculated over the HadCM2 grid centred on 5.63° W using *F*/*Z* threshold values of 4 (HadCM2-GRID$_{5.63W}$-4) and over the original UKTR-grid using *F*/*Z* threshold values of 6 (i.e. the classification from Chapter 2, UKTR-GRID$_{3.75W}$-6) are also shown in Figure 5.15. It is evident that shifting the grid over the Iberian Peninsula and changing the threshold values has major impacts on the observed frequency of occurrence of the circulation types. The cyclonic (C and HYC), unclassified (UC and UA) and northerly (N and NE) circulation types appear most sensitive to changes in the underlying grid and threshold values. As expected, reducing the *F*/*Z* threshold values from 6 to 4 results in a lower frequency of the UC and UA types (compare HadCM2-GRID$_{1.88W}$-6 and HadCM2-GRID$_{1.88W}$-4 in Figure 5.15). Shifting from the UKTR to the HadCM2 grid results in a higher frequency of the UC and UA types (compare UKTR-GRID$_{3.75W}$-6 and HadCM2-GRID$_{1.88W}$-6 in Figure 5.15). Shifting the centre point of the HadCM2 grid from 5.63° W to 1.88° W has an even greater impact on circulation-type frequency, particularly in summer (compare HadCM2-GRID$_{5.63W}$-4 and HadCM2-GRID$_{1.88W}$-4 in Figure 5.15).

It is possible that the variations in circulation-type frequency shown in Figure 5.15 might be related to the use of different constants in the equations used to calculate the flow parameters. However, the same constants are used for all the HadCM2-based grids, so this cannot account for the differences between HadCM2-GRID$_{5.63W}$-4 and HadCM2-GRID$_{1.88W}$-4. Circulation-type frequencies were also calculated using the HadCM2 grid centred on 1.88° W and the constants for the UKTR-grid (i.e. 1.33, 1.05, 0.95 and 0.66). The seasonal cycles for all 14 circulation types (not shown) are virtually identical to those calculated using the HadCM2-grid constants. This suggests that the differences in circulation-type frequency between the different underlying grids are not an artefact of the classification procedure or the grid but may reflect real-world differences in the circulation regime, i.e. the strength of flow tends to be weaker to the south and east of the main Atlantic storm tracks.

Thus mean values of *F* and *Z*, together with the mean frequency of days on which particular threshold values are exceeded, should provide useful parameters for comparing the general characteristics of the circulation classification in different regions. These values, calculated for HadCM2-GRID$_{5.63W}$, HadCM2-GRID$_{1.88W}$, HadCM2-GRID$_{16.88E}$ and HadCM2-GRID$_{28.13E}$, i.e. for a transect centred on 40° N, are shown in Table 5.2. Values for UKTR-GRID$_{3.75W}$ are not shown in the table because the geostrophic units are slightly different. Table 5.2 indicates that there is a gradient in the mean strength of flow (*F*), which initially decreases fairly rapidly with increasing distance from the North Atlantic, i.e. from 5.5 at 5.63° W to 4.8 at 1.88° W. The gradient appears weaker over the western/central Mediterranean, with the mean value of *F* falling slightly to 4.6 at 16.88° E. The strength of flow appears to increase across the Eastern Mediterranean, reaching 5.3 at 28.13° E. Total shear vorticity (*Z*) is relatively high (4.7) at the western end of the transect (5.63° W), but is weaker at the other three points on the transect (which all have the same mean value, 4.2).

The percentage of days on which particular thresholds are exceeded reflects the variations in the mean strength of flow across the transect. Thus the highest occurrence of days when *F*/*Z* is less than 6 (63% at 16.88° E) is associated with the lowest mean *F* value, and the lowest occurrence (45% at 5.63° W) is associated with the highest mean *F* value (Table 5.2).

Table 5.2 indicates that using *F*/*Z* threshold values of 6 would give a classification catalogue for each of the three study regions in which over 50% of days are classified as having indeterminate/light flow (i.e. as UC or UA). This is even greater than the 46% of days classified as UC or UA in the original Guadalentin catalogue (Section 2.2). A scheme in which the majority of days throughout the year are classified as being of one general type (i.e. unclassified or indeterminate flow) is not considered to be particularly skilful or discriminating (although this might be reasonable in summer when conditions tend to be more stable). Sampling and other statistical problems are also likely to occur when classes differ so greatly in size (two circulation types occur on over 50% of days, while the remaining 12 types occupy less than 50% of days), particularly when partitioning data by circulation type and precipitation occurrence. Using *F*/*Z* threshold values of 4 reduces the occurrence of the UC and UA-types to 25-37% of all days (Table 5.2), but there is no physical or other obvious justification for choosing this particular value rather than any other. The choice of threshold values clearly has a major impact on the resulting classification and is discussed further in Section 5.3, taking the performance of HadCM2SUL into account.

5.3 DEVELOPMENT OF A NEW CLASSIFICATION SCHEME BASED ON HADCM2SUL VALIDATION STUDIES

5.3.1 Sea level pressure

In Section 2.4.1 it was demonstrated that, although the UKTR model is reasonably successful in reproducing the main features of the general circulation system over the North Atlantic/European area of interest here, some systematic errors can be identified in the simulated MSLP fields and traced through to errors in simulated circulation-type frequency. Here, the performance of the HadCM2SUL model is assessed using output for 1956-1989 and observed data from the NMC CD-ROM for the same period (interpolated to the HadCM2 grid, as described in Section 5.2.3). Mean seasonal SLP maps for the Northeast Atlantic and Europe calculated from HadCM2SUL output and from the observations are shown in Figure 5.16. Simulated-minus-observed differences are shown in Figure 5.17. A larger European window was available for HadCM2 output than for UKTR output but comparison of Figure 5.17 and Figure 2.7b indicates patterns of error which are common to both models.

In all seasons and both models, a region of negative MSLP anomalies occurs over Greenland, although the magnitude of the anomalies appear somewhat smaller for HadCM2SUL (Figure 5.17) than for the UKTR control run (Figure 2.7b). The reliability of the SLP observations over Greenland is debatable (ACCORD, 2000), but, in part, this region of anomalous values reflects the discrepancies in the shape of the Icelandic Low between the two models and the observations (Figures 2.7 and 5.16). The intensity of the Icelandic Low is, however, better simulated in HadCM2SUL than in UKTR (where it was overestimated). Another notable feature of Figure 2.7b is the region of negative anomalies centred just to the southwest of the British Isles during winter. This anomalous feature only occurs in winter for UKTR, but is evident in winter and spring for HadCM2SUL and covers a larger area in the latter model (Figure 5.17). It may be associated with the errors in the simulation of the Icelandic Low, but also reflects the underestimation of the central pressure, and slight displacement to the east of the Azores High in these seasons (Figure 5.16). Positive MSLP anomalies occur in the north-eastern corner of the European window for UKTR in every season, but are less extensive and smaller in magnitude, or not evident at all, in HadCM2SUL output. The small region of positive anomalies centred over the western/central Mediterranean in autumn seen in UKTR output is also absent in HadCM2SUL. In HadCM2SUL, negative anomalies are centred over the Black Sea area (Figure 5.17), reflecting the underestimation of the westward extent of the Siberian Anticyclone in winter and spring. A new error appears in winter in HadCM2SUL, when most of the Mediterranean region displays positive anomalies. In general, however, global and regional (i.e. Northeast Atlantic/Western Europe) MSLP is considered to be better simulated in the HadCM2 integrations than in the UKTR control run (Johns *et al*., 1997; Corte-Real *et al*., 1999b) and analysis of a 1400-year control run indicates that it exhibits realistic winter-time North Atlantic Oscillation (NAO) spatial patterns (Osborn *et al*., 1999a).

In order to quantify the errors in simulated SLP and compare model performance across the three grids (Figure 5.2), mean seasonal SLP was calculated over the 32 grid points using observed and simulated data. These mean values are shown in Table 5.3, together with their standard deviations. Statistically significant differences between observed and simulated values (calculated using the *t* test for means and the *F* test for standard deviations) are indicated in the table. In winter, simulated MSLP is significantly higher than observed over the Guadalentin and Agri grids, reflecting the area of positive anomalies over the Mediterranean Sea (Figure 5.17). Simulated and observed MSLP values for Lesvos are identical in winter. In every other season, and for all three grids, the simulated values are lower than observed. These systematic differences are statistically significant, except for autumn MSLP over the Guadalentin grid. They are, however, all less than ± 2 hPa, typically about ± 1 hPa. In all cases, except for the Agri in winter, the simulated standard deviations are significantly higher than observed (Table 5.3).

5.3.2 Strength of flow and vorticity

Mean values of simulated and observed resultant flow (*F*) and total shear vorticity (Z) calculated for each of the three study regions for the period 1956-1989 are shown in Table 5.4, together with their standard deviations. Statistically significant differences in the observed/simulated values are indicated (calculated using the *t* test for means and the *F* test for standard deviations). In every case, except for Lesvos in winter, the simulated strength of flow (*F)* is stronger than observed (significantly so except for Lesvos in autumn). All the simulated shear vorticity values (*Z*) are significantly lower (i.e. smaller or more negative) than the observed values. Positive *Z* values are associated with cyclonic flow and negative values with anticyclonic flow (Table 2.1). Thus, although in every season, except winter, simulated mean SLP is lower than observed over the three grids (Table 5.3), the simulated mean *Z* values indicate that mean flow is more anticyclonic than observed in every season. In all but one case (the Agri in winter), the simulated SLP standard deviations are significantly higher than observed (Table 5.3). Similarly in all but one case (winter *Z* in the Guadalentin), the simulated *F* and *Z* standard deviations are significantly higher than observed (Table 5.4).

The observed frequency distributions of the *F* and *Z* parameters are somewhat different in each of the three regions, although all are positively (i.e. right) skewed. Over the year as a whole, the Agri *F* and *Z* distributions have the highest skewness and kurtosis values (1.44 and 2.99 respectively for *F*; 1.67 and 4.71 respectively for *Z*). The *F* distributions for Lesvos have the lowest skewness and kurtosis values (1.04 and 1.48) and the *Z* distributions for the Guadalentin have the lowest values (1.42 and 3.01). As in the Agri, all distributions vary seasonally. The systematic differences in observed/simulated mean values and standard deviations of *F* and *Z* are reflected in the frequency distributions of these parameters. This is illustrated in Figures 5.18 (*F*) and 5.19 (*Z*) for the Agri. The spread of simulated values is greater than observed, giving flatter distributions in all cases. The modal points are also different for the simulated and observed distributions. In the case of *F* (Figure 5.18), the simulated distributions are shifted to the right, reflecting the tendency towards stronger flow in the model. In the case of *Z* (Figure 5.19), the simulated distributions are shifted to the left, reflecting the tendency towards more anticyclonic conditions. Similar differences are seen in the distributions for the Guadalentin and, to a lesser extent, Lesvos (not shown).

The sensitivity of the circulation classifications to the observed mean values of *F* and *Z* and to the choice of threshold values for these parameters was demonstrated in Section 5.2.3. The simulated annual mean values of *F* and absolute *Z* are shown in Table 5.5 and can be compared with the observed values in Table 5.2. This confirms that simulated *F* values are too high and that absolute values of *Z* are also higher than observed. The stronger simulated flow gives a lower percentage of days with *F*/*Z* values exceeding the thresholds of <4 and <6 (an annual maximum of 39% of simulated days (Table 5.5), compared with an annual maximum of 63% of observed days (Table 5.2)). Differences are also evident in the variations in mean *F* and *Z* values across the 40° N transect. In the observations, the minimum mean *F* value occurs over the Agri (16.88° E) and mean absolute *Z* is the same for all three regions. In the model output, however, mean *F* and *Z* values are lowest over Lesvos (28.13° E). Thus the smallest differences between simulated and observed *F* and *Z* values occur over Lesvos. The greatest differences in *F* and *Z* values occur over the Guadalentin and Agri respectively.

5.3.3 Identification of new threshold values

Scatterplots of *F* and *Z* values calculated from the observations and from GCM output have been produced for each of the three study regions. Those for the Agri are shown in Figure 5.20. They confirm the smooth distribution of the *F* and *Z* parameters and the arbitrary nature of the thresholds (6 and 4) used previously. Given this characteristic of the distributions, it was decided to identify new threshold values which might compensate for the systematic errors in the simulated parameters identified in the previous section. These errors vary from region to region, from parameter to parameter and from season to season. Thus it was considered that, rather than using one single value, different threshold values could be used for each region and for each parameter. However, to ensure internal consistency it was decided that the same values should be used for each season. For the Guadalentin basin grid, the annual mean values of observed *F* and absolute *Z* are 4.8 and 4.2 respectively (Table 5.2). These values are within the range of values tested previously (i.e. 4 and 6) and hence it was considered that the mean values might provide appropriate threshold values.

Mean values of *F* and absolute *Z* calculated from the observations and from HadCM2SUL output are shown in Table 5.6 for the three study regions. As expected from the evidence presented in Section 5.3.2, the simulated mean values are consistently higher than the observed values. Mean values of observed and simulated *F* vary from region to region, and the largest simulated minus observed difference (1.6) occurs in the Guadalentin, as expected from Table 5.4. The observed *Z* values are the same for each region (4.2), while the simulated values vary slightly from region to region (from 5.4 to 5.6; Table 5.6).

In Table 5.7, the percentage of days classified as UC or UA using the variable threshold values from Table 5.6 are shown for each season, calculated from the observations and from HadCM2SUL output. Percentages of days obtained using fixed thresholds of 6 and 4 are also shown. With the exception of simulated *F* for the Guadalentin, all the variable threshold values fall within the range of 6-4, hence the percentage of days classified as UC or UA using the Table 5.6 values falls within the range obtained using 6 and 4. In every case, however, the differences between observed and simulated percentages are smaller using the variable thresholds than using fixed thresholds. For Lesvos, the difference, using variable thresholds, is 1-2% in winter, summer and autumn, and a maximum of 9% in summer. The greatest differences (2-24%) still occur for the Guadalentin. In all regions, the greatest percentage differences occur in summer.

The closer agreement between observed and simulated frequencies of days with indeterminate/light flow indicates that the use of the variable threshold values from Table 5.6 does correct, in part, for the systematic GCM errors. However, discrepancies still occur, particularly in summer. Using variable thresholds rather than the original fixed value of 6 reduces the percentage of days classified as UC or UA, from a maximum in the observations of 86% for the Agri in summer to 65%. The reduction in size of the two largest classes is considered advantageous and should result in a more balanced classification.

Two alternative sets of threshold values were tested. First, median rather than mean values were used in order to adjust for differences in the central location of the observed and simulated parameter distributions (see Figures 5.18 to 5.20). This approach gave very similar results to those obtained using mean values and was not pursued. Second, in an attempt to adjust for errors in the shapes of the distributions, daily values of observed and simulated F and Z were standardized using the observed and simulated series means and standard deviations. The 0.5 quantile values calculated from the distributions of standardized F and Z were then used as threshold values. This had a major impact, drastically reducing the frequency of the eight directional circulation types and giving classifications which differed dramatically from all those previously obtained.

Despite these dramatic impacts, the use of standardized flow parameters still does not help with the problem that HadCM2SUL also has a tendency to overestimate the frequency of anticyclonic conditions, i.e. simulated Z values are too negative (see also Wilby *et al*., 1998b; Osborn *et al*., 1999b). In order to correct for this problem, it would also be necessary to change the $Z>2F$ and $F<Z<2F$ rules used to define the C, A, HYC and HYA circulation types (Table 2.1). The extent to which these rules can be modified is, however, limited because anticyclonic flow must occur with negative vorticity, and cyclonic flow with positive vorticity. Thus it was concluded that adjusting for differences in the shape of the observed and simulated distributions of the flow parameters is not feasible or desirable. The use of new threshold values can, therefore, only compensate in part for the systematic errors identified in HadCM2SUL output.

5.3.4 The new classification scheme

Mean annual and seasonal frequencies of the 14 circulation types calculated from the observed data for 1956-1989 using the new, variable, threshold values (i.e. the mean values, see Table 5.6) are shown in Table 5.8 for the three study regions. The corresponding mean seasonal cycles are shown in Figure 5.21. Mean frequencies simulated by HadCM2SUL are also shown in the figure and are discussed in Section 5.6.

For the Guadalentin, the differences in circulation-type frequency between the new classification scheme based on HadCM2-GRID$_{1.88w}$ (Table 5.8; Figure 5.21) and the original classification scheme based on UKTR-GRID$_{3.75w}$ (Table 2.2, Figure 2.4) reflect the shifting of the grid (see Section 5.2.3) and the use of new threshold values (see Section 5.3.3). Shifting the grid causes the mean value of the strength of flow (*F*) and the absolute value of vorticity (*Z*) to decrease (Table 5.2). If the original threshold value of 6 were used with the new grid, this would give a higher percentage of days classified as having light/indeterminate flow. The effect of shifting the grid is, however, more than compensated by the effect of using lower threshold values (4.8 and 4.2 for *F* and *Z* respectively). Thus the main difference between the two classifications for the Guadalentin (Tables 2.2 and 5.8) is the lower number of days classified as having light/indeterminate flow (i.e. UC or UA-types) in the new scheme (a mean of 139 days per annum compared with 170 days in the original scheme). The number of days belonging to one of the eight directional types is virtually identical in the two schemes (115 and 114 days). Thus the lower frequency of the UC and UA-types in the new scheme appears to be directly offset by the higher frequency of the C and HYC-types (an annual mean for the two types of 59 compared with 39 days in the original scheme) and a somewhat smaller difference in the frequency of the A and HYA-types (54 compared with 42 days in the original scheme for the two types). Despite these differences, the UC and UA-types are still the two most frequent individual types over the year as a whole in the new scheme (76 and 62 days respectively).

While the overall number of the eight directional types in the Guadalentin is unchanged in the new scheme (115 days per annum), there are some differences in the frequencies of the individual directional types. Over the year as a whole, the frequencies of the NE, E, SW and W-types are lower in the new scheme than in the original scheme, while the frequencies of the N, SE and NW-types are higher. The mean annual frequency of the S-type is virtually the same in both schemes. Relatively large differences occur in the frequency of the E and NE-types. In the original scheme, these types were combined (Section 2.2.4) and were identified as high rainfall types with a higher than average probability of intense rain days in all seasons (Section 3.2). The implications of the lower frequency of these two circulation types in the new scheme (an annual mean of 22 days compared with 34 days in the original scheme) for circulation-type/rainfall relationships are considered in Section 5.5.1.

While there are differences between the annual frequency of occurrence of the 14 circulation types in the two schemes for the Guadalentin, the shapes of the seasonal cycles are very similar (Figures 2.4 and 5.21). The frequency of the C and HYC-types is low in autumn and winter, increasing in spring with a summer maximum. In comparison, the A and HYA-types have an inverse seasonal cycle, with a winter maximum and summer minimum. The UC-type has the strongest seasonal cycle, with a winter minimum and a pronounced summer maximum. In comparison, the seasonal cycle of the UA-type, which also has a winter minimum, is much weaker. The seasonal cycles of the eight directional types in the Guadalentin are generally weak. The strongest is that of the N-type, which has a winter maximum and a secondary maximum in spring. The NE, SW, W and NW-types have broadly similar, but weak, seasonal cycles, with minima in autumn and summer and higher frequencies in winter.

The seasonal cycles of the six non-directional circulation types are broadly similar in the Agri and Lesvos, and clearly different to those in the Guadalentin (Figure 5.21). While the C and HYC-types have a summer maximum in the Guadalentin, these types have a summer minimum in the Agri and Lesvos and higher frequencies in winter and spring. There is no obvious seasonal cycle in the frequency of the A and HYA-types in the Agri and Lesvos, only a slight spring minimum, whereas these types have a strong seasonal cycle in the Guadalentin with a winter maximum and summer minimum. The seasonal cycles of the UC and UA-types are more similar in the three regions, but are respectively weaker (UC) and stronger (UA) in the Agri and Lesvos compared with the Guadalentin. Interestingly, both these types have a late spring maximum in Lesvos with a reduced frequency in summer, whereas the maximum is in summer/early autumn in the other two regions.

As might be expected, there are greater differences in the seasonal cycles of the directional types across the three regions, although many of these types are infrequent (Figure 5.21). In the Guadalentin the majority of the directional types (i.e. the N, NE, SW, W and NW-types) tend to have maxima in the winter half year and summer minima. This also tends to be the case in the Agri, with the exception of the N-type which has a summer maximum, and to a lesser extent the infrequent NW-type which has a spring maximum. In Lesvos, there is a contrast between the NE and E-types which have complex seasonal cycles with spring minima and the S and SW-types which have simpler seasonal cycles with winter maxima and summer minima. The other directional types in Lesvos are either extremely infrequent and/or have no obvious seasonal cycle.

At the annual level, the percentage of non-directional types is similar in the Guadalentin (69% of all days) and the Agri (70% of all days) but slightly lower in Lesvos (63% of all days). The percentage of the UC and UA-types is similar in the Guadalentin (38% of all days, 55% of non-directional days) and Lesvos (36% of all days, 56% of non-directional days), but higher in the Agri (43% of all days, 62% of non-directional days). While the *Z* threshold values used in all three regions are the same (4.2), the highest *F* threshold value (5.3) is used in Lesvos (which has the lowest number of UC and UA-type days) and the lowest (4.6) is used in the Agri (which has the highest number of UC and UA-type days).

The differences in mean annual circulation-type frequency between the three regions can be summarised as follows. 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, NW-type days.

In comparison to the Guadalentin, Lesvos has:

- more HYA, UA, NE, E and SW-type days; and,
- fewer C, HYC, UC, A, N, SE, W and NW-type days.

It is tempting to speculate about the underlying climatological reasons for the differences in circulation-type frequencies and seasonal cycles between the three regions. A notable characteristic of the Lesvos classification scheme, for example, is the relatively high frequency of the NE and E-types which have complex seasonal cycles (with minima in spring and late autumn/early winter). These features might reflect the influence of the Siberian Anticyclone in winter and that of the low-pressure system over southwest Asia in summer (Bartzokas, 1989). However, the analysis of the original circulation-type scheme for the Guadalentin showed that relationships between the circulation types and the larger-scale circulation can be counter-intuitive (Section 2.3.2). In the original scheme, the cyclonic types (C and HYC), for example, were characterised by a weaker Icelandic Low and less extensive Azores High, while the anticyclonic types (A and HYA) were associated with a deeper Icelandic Low and more extensive Azores High, and hence with high positive values of the NAO index. The NAO is stronger in winter than in other seasons which helps to explain why, against initial expectations (because the Azores High anticyclone is most intensive in summer, see Figure 2.1), the A and HYA-types are more frequent in winter than in summer. Thus it is important to understand the circulation patterns underlying each circulation type before attempting to understand the differences in circulation-type frequency between the three regions.

5.4 EVALUATION OF THE NEW CLASSIFICATION SCHEME

For the new classification scheme to be valid, it is necessary to demonstrate that, for each region in which it is applied, each circulation type has a characteristic underlying synoptic pattern, which is physically distinct and produces the expected type and direction of surface flow (Huth, 1996). This is tested in the same way as for the original scheme, i.e. by constructing composite SLP maps from the NMC CD-ROM data (see Section 2.3.1 for details of the construction methodology). For the Guadalentin (Section 5.4.1), composite maps for the new scheme are compared with those for the original scheme in order to determine whether the new scheme remains valid. For the Agri (Section 5.4.2), more detailed analysis is necessary in order to determine whether the scheme is valid in the new study region. For both regions, composites were constructed for each of the 14 circulation types. To facilitate comparison of the two schemes for the Guadalentin, composites were also produced for the four combined circulation-type groups used in the original scheme. Composite maps were not produced for Lesvos because insufficient daily rainfall data were available for the investigation of circulation/rainfall relationships and hence for the construction of climate-change scenarios. Windows of the same size are used for the Guadalentin and Agri composites. Both extend from 15-85° N. The Guadalentin window extends from 55° W to 35° E, while the Agri window extends from 35° W to 55° E. Thus the study regions are located in the centre of each window.

5.4.1 The Guadalentin

Anomaly SLP composite maps for winter, spring, summer and autumn are shown in Figures 5.22 to 5.25 respectively for each of the 14 circulation types. The corresponding mean SLP maps are shown in Figures 5.26 to 5.29. Anomaly SLP composite maps for the four combined circulation-type groups used in the original scheme (i.e. A/HYA, W/NW/SW/N, E/NE and S/SE) are shown in Figure 5.30. The corresponding mean SLP maps are shown in Figure 5.31.

The winter anomaly patterns for the C, HYC, A and HYA-types are very similar in both schemes, although the magnitude of the anomaly centres tends to be smaller in the new scheme (Figures 5.22a and 5.30a) than in the original scheme (Figure 2.6a). This reflects the use of lower threshold values in the new scheme. Days previously classified as UC and UA are now classified as C or HYC and as A or HYA respectively (see Section 5.3.4). The UC anomaly centres are also weaker in the new scheme than in the original scheme, although the pattern is again very similar (Figures 5.22a and 2.6a). As in the original scheme, the UC anomalies are weakly positive over the study area in spring, summer and autumn. In winter, the area of negative anomalies over the southern Iberian Peninsula (Figure 2.6a) is no longer present in the new scheme (Figure 5.22a). It is unexpected to find positive (high-pressure) anomalies associated with the UC-type, but the anomaly centres are located to the north over the British Isles rather than over the study area and flow over the study area is, by definition, light. Both the pattern and magnitude of the positive UA anomalies are similar in both classification schemes.

The winter anomaly composites for the three directional circulation-type groups (W/NW/SW/N, E/NE and S/SE) are very similar for the new (Figure 5.30a) and original (Figure 2.6a) schemes. The only difference is that the magnitudes of the anomalies are slightly weaker for the W/NW/SW/N and S/SE-type groups in the new scheme. However, the winter composites for the individual directional circulation types in the new scheme (Figure 5.22b) indicate that there are some differences in the anomaly patterns for types which were originally grouped together. In the case of the NE-type, for example, which was originally grouped with the E-type, a negative (low-pressure) anomaly occurs between 0-20° E, extending down into North Africa and across the Mediterranean to Sicily (Figure 5.22b). This anomaly is located further west (extending from about 20°W to 10°E) in the composite for the E-type. The NE-type is more frequent in winter (a mean of 6.2 NE-type days per winter, compared with 2.1 E-type days in the original scheme; 6.1 and 1.2 days in the new scheme), hence the winter anomaly pattern for the E/NE-group (Figures 2.6a and 5.30a) resembles that of the NE-type in the new scheme more closely than that of the E-type. In the new scheme, the winter E-type anomaly pattern is more similar to that of the SE-type than the NE-type, although the magnitude of the negative anomaly centred over the Northwest African coast is considerably larger for the SE-type (Figure 5.22b). The SE-type was originally combined with the S-type. In the composites for the S/SE-type group (Figures 2.6a and 5.30a), the positive (high-pressure) anomaly centred over Scotland and the negative anomaly centred off the Northwest African coast have similar magnitudes. In the new scheme, however, the high-pressure anomaly is stronger than the low-pressure anomaly for the SE-type and *vice versa* for the S-type (Figure 5.22b).

In the original scheme, the W, NW, SW and N-types were grouped together. The winter composites for the new scheme (Figure 5.22b) indicate general similarities between the anomaly patterns for the first three of these types (and similarities between these individual patterns and the W/NW/SW/N-group pattern, see Figures 2.6a and 5.30a), although there are some differences in the magnitude and central location of the extensive low-pressure anomaly in each case. This is strongest and located furthest to the south and the west in the case of the SW-type. The characteristic pattern of these three types (a single large and intensive low-pressure anomaly extending over much of the Northeast Atlantic, Northwest Europe and the Mediterranean) is, however, very different to that associated with the N-type in the new scheme (a relatively weak high-pressure anomaly over the Northeast Atlantic and an even weaker low-pressure anomaly centred over Italy). The N-type is more frequent than the three westerly types in both schemes, which may explain why the low-pressure anomaly for the W/NW/SW/N-group is relatively weak, compared with the anomalies associated with the individual westerly (W, NW and SW) types in the new scheme.

Comparison of the spring and summer anomaly patterns for the original (Figures 2.6b and 2.6c) and new (Figures 5.23, 5.24, 5.30b and 5.30c) schemes leads to similar findings as for winter. In summer, for example, the patterns of the C, HYC, UC and UA-types are very similar in both schemes, but the anomaly centres are again somewhat weaker in the new scheme in summer (Figures 2.6c and 5.24a). Both the pattern and magnitude of the A and HYA-type anomalies are similar in the two schemes in summer (Figures 2.6c and 5.30c). In the new scheme, the NE-pattern is again somewhat different to that of the E-type in summer: it has a weak low-pressure anomaly centred over Italy which does not appear in the E-type composite (Figure 5.24b). In the case of the SE and S-types in summer, the low-pressure anomaly off the Spanish/Northwest African coast is again stronger and more extensive for the latter type. An even more intensive/extensive low-pressure anomaly occurs in a similar location in the summer SW-type composite. Finally, the N-type again has a very different pattern in summer compared with that of the three westerly types (W, NW and SW) with which it was combined in the original scheme.

As a final evaluation of the new scheme, anomaly (Figures 5.25 and 5.30d) and mean pressure (Figures 5.29 and 5.31d) composites are compared for autumn. Autumn is the season in which intense, destructive high rainfall events are most likely to occur in this region of Spain (see Section 3.3) and hence is one of the case studies in Chapter 7. The autumn anomaly maps for the new (Figures 5.25 and 5.30d) and original schemes (Figure 2.6d) support the findings for winter, spring and summer. The C, HYC, UC and UA anomaly patterns are again very similar in both schemes, but the anomaly centres are weaker in the new scheme (Figures 2.6d and 5.25a). The A and

HYA patterns for the new scheme are also very similar to each other, and to that of the combined A/HYA pattern in both schemes, although the anomaly centres are slightly stronger in the original scheme (Figures 2.6d, 5.25a and 5.30d). In the new scheme, the E-type anomaly pattern is again more similar to that of the SE-type than that of the NE-type, and the S and SW-type patterns are more similar than are the S and SE-type patterns (Figure 5.25b). As in winter, spring and summer, the N-type has a very characteristic dipole pattern (a high-pressure anomaly over the Northeast Atlantic and a low-pressure anomaly over Europe) which is very different to that of the three westerly types (SW, W and NW) with which it was combined in the original scheme.

These findings are supported by the mean pressure maps for autumn (Figures 5.29 and 5.31d). The W, NW and SW-types, for example, are all characterised by a low-pressure cell centred over, or just to the southwest, of the British Isles, which is deepest for the W-type and weakest for the NW-type (Figure 5.29b). This pressure pattern is quite different to that of the N-type, which is characterised by high pressure (the Azores High) to the west of the Iberian Peninsula. High pressure is also a feature of the E and SE-types, but in both these cases a high-pressure ridge (indicating a strong and extensive Azores High) extends well to the east over much of Europe and the Mediterranean. The mean autumn pressure patterns associated with the C and HYC and with the A and HYA-types in the new scheme support the interpretation of these composites in the original scheme (see Figure 2.5d and Section 2.3.2). In the C and HYC-type composites, the Icelandic Low appears relatively weak and the Azores High is tilted to the northeast, whereas in the A and HYA-type composites the Icelandic Low is deeper and the Azores High extends right across the Mediterranean basin (Figure 5.29a). Thus the C and HYC patterns again resemble the Greenland Above mode of the NAO, while the A and HYA patterns resemble the Greenland Below mode of the NAO which is associated with high positive values of the NAO index (van Loon and Rogers, 1978; Hurrell, 1995).

The composite maps presented in this section (including the mean pressure maps for winter, spring and summer (Figures 5.26 to 5.28 and 5.31) which are not discussed in the text) indicate that very similar synoptic patterns underlie the circulation types in the original and new schemes for the Guadalentin basin. The major differences between the two schemes occur in terms of the overall frequency (but not the shape of the seasonal cycle) of the circulation types (see Section 5.3.4).

Inspection of all the composite maps for the new scheme confirms that, as in the original scheme, each circulation type produces the expected type and direction of surface flow over the study area. There are, however, similarities between some of the underlying pressure patterns (most notably between the C and HYC-types, the A and HYA-types and the E and SE-types, and to a lesser extent between the S and SW-types and the W and NW-types). The seasonal cycles for these pairs are also similar (Figure 5.21). Each circulation type should have a physically distinct and characteristic underlying synoptic pattern so there are again grounds for combining some of the types, although the composites for the new scheme suggest somewhat different groupings to those used originally. For constructing the weather generator and for downscaling, it is also necessary to ensure that the circulation types are discriminating in terms of their rainfall characteristics. Thus relationships with rainfall in the Guadalentin are considered individually for each circulation type (see Section 5.5.1) before making decisions as to which, if any, types to combine.

5.4.2 The Agri

Anomaly composite maps for the six non-directional types (C, HYC, UC, A, HYA and UA) are shown in Figure 5.32 for the Agri, while the corresponding mean pressure maps are shown in Figure 5.33. Anomaly and mean pressure maps for the eight directional types are shown in Figures 5.34 and 5.35 respectively. With the exception of the UC-type, particularly in winter, each circulation type produces the expected type and direction of flow over the Agri study region. The anomaly patterns associated with each type tend to be similar to those found for the Guadalentin (see Section 5.4.1) but are shifted eastwards. This is expected, because the same grid spacing and typing methodology are used in each case; the grid has simply been shifted 18.76° eastwards. The mean pressure patterns associated with each type are, however, different, reflecting different underlying relationships between flow over the study areas and large-scale features of the atmospheric circulation. Variations in the strength and position of the Icelandic Low and Azores High can be associated with the occurrence of particular circulation types in the Guadalentin Basin (see Sections 2.3 and 5.4.1). In the discussion below, the emphasis is on the identification of links between the Agri circulation types and the large-scale circulation.

The C and HYC-types are characterised by a negative (low-pressure) anomaly centred over southern Italy, the Adriatic and western Balkans and, with the exception of the C-type in winter, a positive (high-pressure) anomaly to the northwest (Figure 5.32). In spring, summer and autumn, this high-pressure anomaly is centred over southwest England, Brittany and the Bay of Biscay. In winter, the high-pressure anomaly associated with the HYC-type is located further to the north over Ireland and Northern Britain (Figure 5.32a). The anomalies are strongest in winter, weakest in summer and of similar magnitude in spring and autumn.

The mean pressure maps for the C and HYC-types (Figure 5.33) show that, as for these types in the Guadalentin (Figures 5.26a, 5.27a, 5.28a and 5.29a), the Azores High is tilted to the northeast. The Icelandic Low appears to be relatively weak, although it extends further eastwards than in the Guadalentin composite. (Note, however, that the Agri composite window does not extend as far west as the Guadalentin window. This makes it difficult to fully compare the behaviour of the Icelandic Low in the two classification schemes.) In spring and summer (Figures 5.33b,c), the low pressure over the Agri may be related to the extension of the southwest Asian low-pressure system (a dominant feature of summer circulation – Meteorological Office, 1962; Bartzokas, 1989) over North Africa and the eastern Mediterranean. In autumn, a trough extends northwestwards across the central and eastern Mediterranean from Egypt/the Middle East to northern Italy (Figure 5.33d). This low-pressure feature appears to be ‘squeezed’ between the Azores High to the west and the extension of the Siberian Anticyclone to the east (a dominant feature of the winter half-year circulation; Bartzokas, 1989). A similar pattern occurs in winter, although in this season the low-pressure area over Italy appears to be more of a ‘cut-off’ feature (Figure 5.33a). The occurrence of a trough dividing the Azores High and Siberian Anticyclone is a characteristic feature of the Mediterranean circulation from November to March (Meteorological Office, 1962) and is likely to explain, in part, why the C and HYC-types have a maximum frequency in the winter half of the year (Figure 5.21).

Although the pattern of anomalies is generally similar for the Guadalentin (Figure 5.22a) and the Agri (Figure 5.32a) C and HYC-types, the high-pressure anomaly is weaker (in the case of the HYC-type) or absent (in the case of the C-type) in the Agri in winter. Inspection of the mean pressure maps also indicates that, although relatively weak, the Icelandic Low is stronger and extends further eastwards for the Agri C and HYC-types (Figure 33a) than for the Guadalentin C and HYC-types (Figure 5.26a). Similarly, in summer, the Azores High extends further eastwards in the composites for the Agri C and HYC-types (Figure 5.33c). These differences may also help to explain why the C and HYC-types have a maximum in the winter half of the year in the Agri (when the Azores High is weaker) but a pronounced summer maximum in the Guadalentin (Figure 5.21).

The A and HYA-type anomaly patterns (Figure 5.32) are the reverse of the C and HYC-type patterns, with high pressure over southern Italy and low pressure to the north and northwest. This pattern is very much stronger in winter than in other seasons. The high-pressure anomaly is in a similar position and has a similar shape in all seasons, while the low-pressure anomaly shows more variation in size and position from season to season. From the mean pressure maps (Figure 5.33), it is less easy to identify consistent relationships between the A and HYA-types and the large-scale circulation than between the C and HYC-types and the large-scale circulation (or between the Guadalentin A and HYA-types and the large-scale circulation). In the case of the A-type in winter (Figure 5.33a) and the A and HYA-types in autumn (Figure 5.33d), for example, the high-pressure area over the Agri occurs in a general belt of high pressure which extends from the Azores High in the west to the Siberian Anticyclone in the east. The winter HYA-type may reflect an eastwards extension of the Azores High, but note that, in this season, the HYA-type pressure pattern is rather similar to those of the UC and UA-types (Figure 5.33a). Overall, the high pressure over southern Italy in the A and HYA-composites appears to be more of a local feature than the high-pressure area associated with these types in the Guadalentin (which is more clearly related to extensions of the Azores High, see Figures 5.26a, 5.27a, 5.28a and 5.29a). This may be why the A and HYA-types are relatively infrequent in the Agri compared with the Guadalentin (Table 5.8). The lack of systematic relationships with features of the large-scale circulation may also explain the lack of a seasonal cycle in the frequency of occurrence of the A and HYA-types in the Agri, compared with the strong seasonal cycle observed in the Guadalentin (Figure 5.21).

The UC and UA-type anomaly maps for spring, summer and autumn (Figure 5.32) indicate weak flow over the Agri, as expected, although the anomalies to the north of the study area associated with the UC-type are weakly positive rather than negative as expected. Weakly positive anomalies also occur in the UC-type composites for the original Guadalentin scheme (Figure 2.6), except in winter, and for the new Guadalentin scheme (Figure 5.22). In the Agri, positive anomalies also occur in winter in the both the UC and UA composites (Figure 5.32a) and are stronger than in other seasons. The winter UA-type anomaly centre is of comparable magnitude to that of the HYA-type. The mean winter pressure maps (Figure 5.33a) for the UA and HYA-types are also very similar. In winter, the positive anomaly in the UC composite is centred over the Agri rather than to the north as in other seasons and is stronger. This suggests that the UC-type may be poorly classified in winter. Note, however, that the frequency minimum for this type occurs in winter (Figure 5.21).

As was found for the six non-directional types discussed above, the anomaly patterns associated with the eight directional types in the Agri (Figure 5.34) are similar to those for the Guadalentin (Figure 5.22) but are shifted eastwards and tend to be somewhat weaker in magnitude. Thus the N-type is again characterised by high pressure to the west of the study region (in this case, the anomaly is centred over the western Mediterranean basin) and low pressure to the east (with the anomaly centred over the Black Sea). This is the only directional type to have a frequency maximum in summer. The NE-type is characterised by a high-pressure anomaly extending over central Europe and the central Mediterranean, and, except in summer, a weaker low-pressure anomaly extending over Turkey and the Middle East. The E and SE-types are both characterised by an extensive high-pressure anomaly covering most of Europe. In some cases (the SE-type in winter, E and SE-types in spring and the SE-type in summer) a small and weak negative anomaly also appears over North Africa. Note that the E-type does not occur in the summer months and hence composite maps are not available for this season. The S-type is characterised by a low-pressure anomaly over southwest Europe and a high-pressure anomaly to the northeast over eastern Europe/Russia/Scandinavia. The SW, W and NW-types are all characterised by negative anomalies which are most intensive and extensive in winter and autumn.

Inspection of the actual pressure maps (Figure 5.35) indicates that the N and NE types are associated with the eastwards extension of the Azores High. The high-pressure ridge extends furthest east in the NE-type composite particularly in spring and summer (Figures 5.35b,c). The seasonal frequency cycle of the two types is also different (Figure 5.21). Except in summer when it occurs very rarely (Table 5.8, Figure 5.21), the S-type is associated with high-pressure extending from the east, i.e. from the Siberian Anticyclone (Figure 5.35). In winter and autumn, the extensive high-pressure anomaly characterising the E and SE-types is associated with a general belt of high pressure extending from the Azores high in the west to the Siberian Anticyclone in the east (Figures 5.35a,d). These types are less frequent in spring and summer (Table 5.8, Figure 5.21). The E-type does not occur at all in summer. When it does occur in summer, the SE-type appears to be associated with an extended Azores High (Figure 5.35c). The low-pressure features associated with the SW, W and NW-types vary from relatively deep lows over southern Scandinavia (in the case of the W and NW-types in winter) through to general low pressure over central/northeast Europe (in the cases of the SW-type in winter, the SW and NW-types in spring and all three types in summer).

The underlying pressure patterns for all three types are similar in autumn (Figure 5.35d): an area of low pressure over Scandinavia, with high-pressure ridges to the southwest (the Azores High) and the southeast (the Siberian Anticyclone).

As in the Guadalentin (Section 5.4.1), there are similarities between some of the individual types in the Agri, both in terms of their underlying pressure patterns (this section) and their frequency over the seasonal cycle (Section 5.3.4; Figure 5.21). The C and HYC-types are again similar, although their underlying pressure patterns are less similar in winter than in other seasons. The A and HYA-type composites and seasonal cycles are similar in all seasons. Rather fewer of the directional types are similar in the Agri compared with the Guadalentin and slightly different groupings are suggested. The E and SE-types are similar, for example, and, to a lesser extent, the SW and W-types. As in the Guadalentin, however, it is necessary to determine whether particular types are similar in terms of their rainfall characteristics (considered in Section 5.5.1 for the Guadalentin and Section 5.5.2 for the Agri) before taking decisions about whether or not to combine them.

5.4.3 Discussion

With the exception of the UC-type in winter in the Agri, all the composite maps presented in Sections 5.4.1 and 5.4.2 indicate that each circulation type produces the expected type and direction of flow over the two study areas. The problem with the UC-type is not considered serious because flow is, by definition, light for this type and it occurs relatively infrequently in winter.

While the anomaly patterns over the two study areas are constrained to be broadly similar by the typing methodology, there are differences in the underlying relationships between flow over each study area and the large-scale circulation. In the Guadalentin, for example, the influence of the NAO is evident in the C and HYC-types (which are associated with the Greenland Below mode of the NAO) and the A and HYA-types (which are associated with the Greenland Above mode of the NAO and with high positive values of the NAO index). The influence of the NAO is less evident in the Agri, although variations in the intensity and extent of the Azores High are important. In this more easterly study region, the seasonal influences of the Siberian High (which is strongest in winter) and the southwest Asian low-pressure system (which is strongest in summer) are evident, together with more localised Mediterranean influences. These differing influences may help to account for some of the major differences in the seasonal cycle of occurrence of some of the circulation types (possible reasons for the different seasonal cycles in the two regions for the C, HYC, A and HYA-types are discussed in Section 5.4.2).

Analysis of the composite maps indicates that it is valid to apply the circulation typing scheme in both areas, although it may be desirable to group some of the more similar circulation types together. In evaluating the suitability of a typing scheme for downscaling purposes, however, the requirement for each type to have a characteristic and physically distinct underlying synoptic pattern is only one of the necessary criteria. The extent to which the typing schemes are also discriminating in terms of the rainfall characteristics associated with each type is considered in the next section.

5.5 CIRCULATION/RAINFALL RELATIONSHIPS IN THE GUADALENTIN AND AGRI

5.5.1 The Guadalentin

Rainfall contributions

As a first step in the investigation of circulation/rainfall relationships, the mean annual frequency of each of the 14 circulation types was compared with the percentage contribution to total annual rainfall at each of the six Guadalentin Basin stations (Figure 5.36). Note that the station of Aguilas used in the evaluation of the original scheme (see Section 3.2) is replaced by Embalse de Cierva (see Section 5.2.1) for evaluation of the new scheme.

As in the original scheme (Figure 3.6), it is possible to identify circulation types for which the contribution to annual rainfall is considerably greater (or less) than average (Figure 5.36). The C and HYC-types both occur on about 8% of days, but both contribute about 15-20% of total rainfall. The percentage contributions to annual rainfall of the NE, E and SE-types are also greater than the percentage of days on which they occur. Most notably, the E-type occurs on less than 2% of days but contributes 10-13% of annual rainfall. The percentage contribution from the S-type is similar to its percentage occurrence. For all other types (UC, A, HYA, UA, N, SW, W and NW), the percentage rainfall contribution is lower than their percentage occurrence. The difference between the two percentages is not large for the UC, SW and W-types, but is considerable for the other types. The A-type, for example, occurs on about 7% of days but contributes 1% or less of total annual rainfall.

Seasonal circulation-type frequencies and rainfall contributions are shown in Figure 5.37. Some relationships, such as those for the E and SE-types, are clearly consistent from season to season, although the relative difference between the two percentages may vary. The percentage contribution from the C and HYC-types, for example, is greater than their percentage occurrence in every season, although less so in autumn than in other seasons. The UC-type is more variable (as it was in the original scheme, Figure 3.7). The percentage rainfall contribution is less than the percentage occurrence in summer only (the season in which this type is most frequent, Table 5.8). The two percentages are similar in spring, but in winter and autumn, the percentage contribution is greater than the percentage occurrence. The seasonal relationships also tend to vary more from station to station compared with the annual relationships. The NE-type, for example, occurs on about 7% of days in winter and contributes 17% of total rainfall at Fuente Alamo, but only 6% at Embalse de Cierva.

Rainfall probabilities/intensities

The high percentage rainfall contributions from the C, HYC, NE, E, SE and, in winter and autumn, the UC-types may be because a high proportion of days of these types are wet, and/or because there is a large amount of rainfall on each wet day. These two possibilities are investigated, as for the original scheme (see Section 3.2.3), using annual and seasonal $PROP_{ct}/PROP_{tot}$ (Figures 5.38 and 5.39) and $PREC_{ct}/PREC_{tot}$ (Figures 5.40 and 5.41) ratios respectively. For a circulation type with a ratio greater (less) than 1.0, the likelihood of rain (in the case of $PROP_{ct}/PROP_{tot}$) or the amount of rain per rain day (in the case of $PREC_{ct}/PREC_{tot}$) is greater (lower) than the station mean.

The likelihood of rain associated with the C, HYC, E and SE-types is greater than the station mean (i.e. $PROP_{ct}/PROP_{tot} > 1.0$) over the year as a whole (Figure 5.38) and in every season (Figure 5.39). Conversely, the likelihood of rain associated with the A, HYA, UA and NW-types is always less than average. The ratios for the other types are more variable from season to season (Figure 5.39). Thus, additional types with a greater than average likelihood of rain appear in winter (the UC, S and SW-types) and in autumn (the NE and S-types). The likelihood of rain for the NE, S and SW-types is either close to average or slightly below average in other seasons (Figure 5.39), and slightly greater than average over the year as a whole (Figure 5.38). $PROP_{ct}/PROP_{tot}$ ratios for the N and W-types are either close to or below average in all seasons. The UC-type is more variable, having a higher than average likelihood of rain in winter, a lower than average likelihood in summer and close to average likelihood in spring and autumn.

The $PREC_{ct}/PREC_{tot}$ ratios show more variability from season to season (Figure 5.41) and from station to station. Over the year as a whole (Figure 5.40), and in winter, spring (with the exception of Embalse de Cierva) and autumn, the amount of rain per rain day is higher than average for the E and SE-types. It is also higher than average at the majority of stations for the UC and NE-types in winter, the C and HYC-types in spring and the UC-type in autumn. In summer, the only type for which the amount of rain is higher than average at all stations is the HYC-type. Rainfall intensity tends to be below average at the majority of stations and in most seasons for the following types: A, HYA, N, S, SW, W and NW.

The circulation type/rainfall relationships identified from Figures 5.38 to 5.41 are summarised in Table 5.9. The most important high-rainfall types are the C, HYC, E and SE-types and, to a lesser extent, the UC, NE and S-types. The C and HYC-types have a high proportion of wet days of average intensity, while the E and SE-types have a high proportion of wet days of high intensity. The exception to this pattern is in summer, when the HYC-type has a high proportion of wet days of high intensity, whereas E and SE-type wet days are of average rather than high intensity. The A, HYA, UA, N, SW, W and NW-types are all consistent low-rainfall types, with a low proportion of wet days of either average or below average intensity.

These relationships are similar to those identified for the original Guadalentin circulation-type groups. The main difference, for the types which can be directly compared, is that the UC-type appears less important as a high-rainfall type in the new scheme. This might be expected, because this type is less frequent (an annual mean of 76 days compared with 91 days in the original scheme) and is associated with weaker flow (because lower F and Z threshold values are used) than in the original scheme. It appears that some UC-type days are re-classified as C and HYC-type days in the new scheme (see Section 5.3.4). These must be days with relatively stronger flow and their inclusion in the more frequent C and HYC categories (31 and 28 days per annum respectively, compared with 19 days each in the original scheme) does not affect the rainfall characteristics of these types (which still appear as high-rainfall types). The E and NE-types are less frequent in the new scheme (16.1 and 5.8 days per annum respectively, compared with 22.3 and 11.2 days in the original scheme), but these two types both remain important high-rainfall types.

Examination of the rainfall characteristics of the types which were originally grouped together indicates that some of the individual types do not share the same characteristics. The S-type was originally grouped with the SE-type. It has a higher than average proportion of rain days in winter and autumn and over the year as a whole, whereas the SE-type has a higher proportion of rain days in all seasons. Furthermore, rainfall on S-type days tends to be of below average intensity, whereas SE-types tend to be of above average intensity. The composite anomaly and pressure maps for these two types are also somewhat different (Section 5.4.1). The SE-type rainfall characteristics and composites are much more similar to those of the E-type, which was originally grouped with the NE-type. Although the NE-type is identified as a high rainfall type in Table 5.9, it is less important than the E and SE-types and has a somewhat different underlying pressure pattern (Section 5.4.1). The SW-type was originally grouped with the low-rainfall W, NW and N-types. Unlike the other three types, however, it has a higher than average proportion of wet days in winter and composite maps which more closely resemble those of the S-type. Thus consideration of the rainfall characteristics associated with each circulation type supports the conclusion from the analysis of the underlying pressure patterns in Section 5.4.1, that more appropriate groupings can be identified (i.e. C and HYC, A and HYA, E and SE, S and SW, W and NW) than those used for the original scheme (A/HYA, W/NWSW/N, E/NE and S/SE). This issue is discussed further in Chapter 6.

Evaluation of the relationships

The identification of the cyclonic circulation types (C and HYC) as important high-rainfall types and the anticyclonic circulation types (A, HYA and UA) as major low-rainfall types is not surprising from a basic meteorological point of view. However, the evaluation of circulation-type/rainfall relationships for the original Guadalentin scheme (see Section 3.3) indicates that there are more specific, synoptic reasons for the different characteristics of these types. The arguments from Section 3.3 can be summarised as follows:

- Relationships exist between the C and HYC-type anomaly patterns, the Greenland Above mode of the NAO and high-pressure blocking in the Northeast Atlantic.
- These features result in a more meridional circulation, with more frequent troughs and incursions of polar air over the Mediterranean and the southward displacement of the Atlantic storm tracks.
- All these factors are conducive to wetter conditions in the western Mediterranean.
- Conversely, relationships exist between the A and HYA-type anomaly patterns, the Greenland Below mode of the NAO and high positive values of the NAO pressure index.
- Under these conditions, moisture transport across the North Atlantic has a more southwest-to-northeast orientation and rainfall is reduced over southern

Europe and the Mediterranean.

- These contrasting relationships are reflected in the negative correlations found between rainfall over the Iberian Peninsula and the NAO index (Hurrell, 1995; Rodo *et al*., 1997; Esteban-Parra *et al*., 1998).

This interpretation of the C, HYC, A and HYA-types is considered to remain valid for the new scheme. Although they have a higher proportion of wet days, the C and HYC-types do not generally have a higher than average amount of rainfall on a wet day (Table 5.9), suggesting that the rain is associated with frontal events rather than with high-intensity convective events and also reflecting the short sea track across the Mediterranean. The major exception is the HYC-type in summer, when rainfall intensity is above average at all stations. This may reflect the occurrence of convective events in summer.

The relationships between rainfall and the two light-flow types, UC and UA, are somewhat different (Table 5.9). As expected from its pressure composites (see Section 5.4.1), the UA-type consistently has a lower than average proportion of rain days and rain per rain day is consistently below average in every season except winter. Somewhat surprisingly, the UC-type has a higher than average proportion of rain days in winter and the composite for this season is characterised by a high-pressure anomaly over the study area (Figure 5.22). However, this type occurs on less than four days per winter on average (Table 5.8). Over the year as a whole, the UC-type contributes relatively less rainfall than its percentage occurrence in the new scheme compared to the original scheme. This is expected because of the weaker flow associated with the use of a lower threshold value in the new scheme.

In the case of the directional types in the new scheme, the construction of composite maps for the individual circulation types and the analysis of individual circulation-type/rainfall relationships, rather than grouping types together as in the original scheme, enables a more detailed analysis to be made and demonstrates the sensitivity of this relatively sheltered region of Spain to the direction of surface flow (Romero *et al*., 1998).

Atlantic influences are relatively strong over much of Spain (Rodo *et al*., 1997; Esteban-Parra *et al*., 1998; Rodriguez-Puebla *et al*., 1998; Serrano *et al*., 1999), but in the southeastern region it is possible to distinguish between the relatively weak influence on the precipitation regime of Atlantic air flows and the stronger influence of Mediterranean air flows (Lines Escardó, 1970; Wheeler and Martin-Vide, 1992; Romero *et al*., 1998). By the time Atlantic air masses associated with the W and NW-types have crossed the Iberian Peninsula and reached the Guadalentin region their moisture content is likely to be considerably reduced and thus they will be ineffective as rainfall producers in this region (Romero *et al*., 1998). This is also likely to be the case for air masses associated with the N-type, which face the additional barrier of the Pyrenees. The NE-type was grouped with the E-type in the original scheme, but examination of the composite maps for this individual type (Figures 5.22b to 5.25b and Figures 5.26b to 5.29b) shows that the air masses associated with it tend to have a land track rather than a sea track. In addition, the Guadalentin region is sheltered from this direction of flow by the Sierra de Aitana range immediately to the northeast (Romero *et al*., 1998). Thus this type is considerably less important as a high-rainfall type than the E and SE-types (Table 5.9).

The importance of easterly and southeasterly surface flow for rainfall in this region of Spain is widely recognised (see discussion in Section 3.3; Romero *et al*., 1999a; 1999b; Serrano *et al*., 1999). Air masses from this direction have a long track across the Mediterranean Sea, allowing surface and near-surface air masses to pick up more moisture and heat, particularly in autumn when sea surface temperatures are highest. Rainfall is very likely to occur when such warm moist air masses meet the coastal ranges. These events are likely to be convective, but the favourable combination of topography and direction of surface flow provides the conducive conditions in which they are most likely to occur (Romero *et al*., 1998; Romero *et al*., 1999a). However, the occurrence of troughs or lows at upper levels, and hence cold air incursions over the Iberian Peninsula, is also recognised as a contributory factor (with easterly/southeasterly surface flow) for intense rainfall events in this region (see Section 3.3; Romero *et al*., 1998; 1999a; 1999b). The occurrence of such upper-air features in association with the E and SE-types is considered in Chapter 7, focusing on intense autumn rainfall events. On some occasions, rainfall may occur in this region with very weak flow at low levels but with cold air aloft (Romero *et al*., 1999a). This could explain why the UC-type appears as a high-rainfall type in winter (Table 5.9). It could also help to explain the occurrence of intense rainfall events on HYC-type days in summer, although these may be more purely convective events.

The final two directional types, S and SW, both tend to be associated with rainfall of below average intensity, but have a higher than average proportion of rain days in winter (S and SW-types) and autumn (S-type). The composites indicate that both these types have short sea tracks across the Mediterranean (Figures 5.22b to 5.25b and Figures 5.26b to 5.29b) which is likely to be why the amount of rain on these days is relatively low. It is also possible that flow from these directions is associated with Atlantic depressions funnelled through the Straits of Gibraltar or with depressions formed in the Gulf of Cadiz (see Section 3.3).

In general, the observed circulation/rainfall relationships for the new Guadalentin Basin scheme can be explained in terms of the underlying synoptic situation, i.e. in terms of physical mechanisms. This helps to increase confidence in the validity of the scheme for the classification of observed climate and for downscaling applications. There are, however, questions about some of the relationships (such as those of the HYC-type in summer and the UC-type in winter) and the role of upper-air circulation (particularly in relation to intense rainfall events). Some of these issues are addressed further in Chapter 7.

5.5.2 The Agri

Rainfall contributions

Once again, as a first step in the investigation of circulation/rainfall relationships, the mean annual frequency of each of the 14 circulation types was compared with the percentage contribution to total annual rainfall at each of the stations in the study region (Figure 5.42). Eleven stations were used for the Agri, reflecting the strong precipitation gradient from the dry, low-altitude eastern end of the basin to the wetter, higher western end (see Section 5.2.2). The data period, for which both NCEP SLP and daily precipitation data are available, is 1956-1988 (but note that three of the station series end in 1977 or 1978, Table 5.1).

As in the Guadalentin, it is possible to identify circulation types for which the contribution to annual rainfall is considerably greater (or less) than average (Figure 5.42). The C and HYC-types both occur on about 10% of all days but contribute about 26-30% and 21-24% respectively of total precipitation at all stations. The only other type for which the percentage contribution is consistently greater than or equal to its percentage occurrence is the SE type. This type occurs on about 4% of days and its percentage rainfall contribution varies from about 4% at Moliterno (the westernmost of the Agri stations, Figure 5.4) to 15% at Nova Siri Scalo (the easternmost station).

Regional differences are also apparent for many of the other directional types. For the S-type, for example, the percentage rainfall contribution is greater than the percentage occurrence at four stations: Nova Siri Scalo, Pisticci, Tursi and Stigliani. The first three of these stations are the three easternmost stations, while Stigliani is located on the high south-facing ridge to the north of the river (Figures 5.3 and 5.4).

For the SW and W-types, the percentage rainfall contribution is greater than the percentage occurrence at three stations: Moliterno, Corleto Perticara and San Martino d'Agri. These are the three westernmost stations. Moliterno also appears as a slight exception for the E-type (it is the only station where the rainfall contribution is lower (albeit only slightly) than the percentage occurrence) and the NW-type (it is the only station where the rainfall contribution is (slightly) greater than the percentage occurrence). For all the other types (UC, A, HYA, UA, N and NE) the percentage occurrence is greater than the percentage rainfall contribution at all stations.

Seasonal circulation-type frequencies and rainfall contributions are shown in Figure 5.43. The C and HYC-types have a greater rainfall contribution than percentage occurrence in every season, although the difference between the two percentages is smaller in summer than in other seasons. The UC-type has a smaller rainfall contribution than percentage occurrence in winter and autumn, broadly similar percentages in spring, and, except at Moliterno, a greater rainfall contribution than percentage occurrence in summer. The A, HYA and UA-types have a smaller rainfall contribution than percentage occurrence in all seasons, although the difference between the two percentages is smallest in summer. The main characteristic of the Agri classification scheme in summer is the very low frequency of the directional types (particularly the E, SE, S, SW and W types) and of the A and HYA-types (Table 5.8; Figure 5.21). UC or UA-types occur on 66% of summer days (Table 5.8). The UC-type contributes 31-45% of summer rainfall and the UA-type contributes an additional 13-26%. Figure 5.43 also indicates some smaller seasonal variations in the influence of some of the directional types. The SE-type, for example, contributes relatively more to rainfall in winter and autumn than in spring and summer. The S and SW-types tend to contribute relatively more in autumn than in other seasons.

Rainfall probabilities/intensities

$PROP_{ct}/PROP_{tot}$ and $PREC_{ct}/PREC_{tot}$ ratios (see Sections 3.2.3 and 5.5.1) are used to identify circulation types for which the likelihood of rain or the amount of rain per rain day is greater or less than the station mean. Annual $PROP_{ct}/PROP_{tot}$ and $PREC_{ct}/PREC_{tot}$ ratios for the eleven Agri stations are shown in Figures 5.44 and 5.45 respectively. In order to investigate the stationarity of circulation/rainfall relationships, which are of particular interest given the time-dependent trends towards decreasing rainfall in the Agri (see Section 5.2.2 and Figure 5.13), ratios are also shown for three sub-periods: 1956-1968, 1969-1978 and 1979-1988. Note that the series for Corleto Perticara, Moliterno and Stigliano end in 1977 or 1978 (Table 5.1), hence ratios for these stations are not available for the most recent sub-period.

Over the complete data period, the probability of rain is greater than average for the C, HYC and SE-types at all stations (Figure 5.44a). The highest ratio values are those for the C-type. The probability of rain is also greater than average for the E-type at every station except Moliterno. This station also has the lowest ratio (though still greater than 1.0) for the SE-type, while the northeastern stations of Pisticci and Stigliano have the highest ratios for this type. The likelihood of rain is less than average at every station for the UC, A, HYA, UA and N-types. Regional differences are evident in the ratios for the SW and W-types. For the SW-type, for example, the likelihood of rain is less than average at the eastern stations of Nova Siri Scalo, Pisticci and Tursi and at the northeastern station of Stigliano. The highest likelihood of rain associated with the SW-type occurs at the westernmost stations of Moliterno and San Martino d'Agri. The contrast between western and eastern stations and their relationships with the SW and W-types is strongest in the sub-period 1956-1968 (Figure 5.44b) and less distinct in the other two sub-periods (Figures 5.44c and 5.44d). In general, however, the $PROP_{ct}/PROP_{tot}$ ratios, particularly for the non-directional types, appear fairly stable over the three sub-periods.

Over the full data period, the amount of rain per rain day is greater than average at all stations for the C and HYC-types and less than average at all stations for the UC, A, HYA, UA, N and NE-types (Figure 5.45a). There is no directional type with a $PREC_{ct}/PREC_{tot}$ ratio greater than 1.0 at all stations. The amount of rain per rain day associated with the E-type is less than average at Moliterno and Corleto Perticara at the western end of the basin and, more surprisingly, at Nova Siri Scalo at the eastern end. For the SE-type, however, there is a large contrast between Moliterno (and to a lesser extent Corleto Perticara and San Martino d'Agri) with low intensity rainfall and Nova Siri Scalo with high intensity rainfall. For the SW and W-types, as for probability of rain, there is a contrast between the westernmost stations (Moliterno, Corleto Perticara and San Martino d'Agri) with greater than average rain per rain day and the other stations with less than average rain.

The amount of rain per rain day varies more between the three sub-periods (Figures 5.45b-d) than rainfall probability (Figures 5.44b-d), particularly for the relatively infrequent directional types, but the relationships remain broadly comparable. The amount of rain associated with the SE-type at Nova Siri Scalo is much lower for the 1956-1968 sub-period (Figure 5.45b) than for the other two sub-periods, for example. During the driest sub-period, 1979-1988 (see Section 5.2.2), $PREC_{ct}/PREC_{tot}$ ratios tend to be higher than in other sub-periods for the ‘low-rainfall’ A, HYA, UA, N and NE types and lower than other sub-periods for the ‘high-rainfall’ HYC type.

The percentage contributions (Figures 5.42 and 5.43), together with the $PROP_{ct}/PROP_{tot}$ and $PREC_{ct}/PREC_{tot}$ ratios (Figures 5.44 and 5.45) and the scatter plots in Figures 5.5 to 5.7, indicate that there are more systematic spatial variations in rainfall and in relationships between the directional circulation types and rainfall across the Agri basin than in the Guadalentin (see Sections 5.2.2 and 5.5.1). This is illustrated further in Figures 5.46 and 5.47 which show the $PREC_{ct}/PREC_{tot}$ ratios for the SE and W-types plotted against longitude for the Agri and Guadalentin respectively. In the Agri (Figure 5.46), the intensity of rainfall on SE-type days increases from west to east across the basin, while the intensity of rainfall on W-type days decreases from west to east. In the Guadalentin (Figure 5.47), rainfall intensity is consistently above average at all stations on SE-type days and below average on W-type days. The SE and W-types were selected to illustrate this feature of circulation/rainfall relationships because the $PREC_{ct}/PREC_{tot}$ ratios for these types in the Agri show the greatest inter-station variability (Figure 5.45). It is not possible to identify any such systematic inter-station variability in any of the ratios for the Guadalentin (Figures 5.38 to 5.41).

The new weather generator was used to develop climate-change scenarios for one baseline station in each basin (see Chapter 6). Here, therefore, circulation/rainfall relationships for the Agri baseline station, Missanello, are investigated in further detail. Missanello was selected because it is centrally-located in the basin (Figure 5.3) and has a long record (1951-1992) with very few missing values.

Annual $PROP_{ct}/PROP_{tot}$ and $PREC_{ct}/PREC_{tot}$ ratios for Missanello for 1956-1988, together with ratios for the three sub-periods (1956-1968, 1969-1978 and 1979-1988), are shown in Figures 5.48 and 5.49 respectively. The probability of rain at Missanello is greater than average for the C and HYC-types and, to a lesser extent, for the E and SE-types and also for the SW and W-types. It is close to average for the NE and S-types and less than average for the UC, A, HYA, UA, N and NW-types. The amount of rain per rain day is greater than average for the C and HYC-types, although the $PREC_{ct}/PREC_{tot}$ ratio values are not as high as the $PROP_{ct}/PROP_{tot}$ values. Thus these types have a high probability of fairly intense rainfall. The SE and E-types also have a greater than average amount of rain per rain day, except in the case of the E-type during 1979-1988, and the $PREC_{ct}/PREC_{tot}$ ratio values tend to be higher than for the C and HYC-types. Thus these types have a high probability of intense rainfall. The SW and W-types have $PREC_{ct}/PREC_{tot}$ ratios of less than 1.0 and $PROP_{ct}/PROP_{tot}$ ratios of greater than 1.0, thus they have a high probability of low-intensity rainfall.

Figures 5.48 and 5.49 demonstrate that the amount of rain per rain day and the rainfall characteristics of the relatively infrequent directional circulation types are more variable over time than are the probability of rain and the rainfall characteristics of the more frequent non-directional circulation types.

The seasonal ratios $PROP_{ct}/PROP_{tot}$ and $PREC_{ct}/PREC_{tot}$, shown in Figures 5.50 and 5.51 respectively for Missanello, show greater variability than the annual plots. Note that it is not possible to calculate ratios for some circulation types because no rainfall occurs at Missanello on that particular type day in a particular season. The temporal variability seen in the seasonal ratios may reflect the small sample sizes and/or the occurrence of a few extreme events, or some non-stationarity in the circulation/rainfall relationships. In order to demonstrate whether either of the first two reasons may be applicable, four outlier $PREC_{ct}/PREC_{tot}$ ratio values were investigated:

i. The high winter SE-type ratio in 1979-1988 (Figure 5.51a);
ii. The high spring E-type ratio in 1956-1968 (Figure 5.51b);
iii. The high summer NE-type ratio in 1969-1978 (Figure 5.51c); and,
iv. The high autumn E-type ratio in 1969-1978 (Figure 5.51d).

Outlier (i) was calculated by averaging over 19 rain days. These include two major events in December 1984. On 4th and 5th December, 90 mm of rain fell, with a further 117 mm on 29th and 30th December, i.e. 78% of mean winter rainfall (and 26% of mean annual rainfall) fell on just four days. Torrential rainfall events are a characteristic feature of the rainfall regime in the Basilicata region of southern Italy (Cantú, 1977). For example, during the time series used here, more than 300 mm of rain fell in a single day at Pisticci (315 mm on 25 November 1959, 59% of mean annual rainfall) and at Stigliano (305 mm on 19 January 1972, 38% of mean annual rainfall). The November 1959 event occurred on a day classified as a S-type day and affected the eastern end of the basin. The January 1972 event occurred on a day classified as a HYC-type day. It affected the whole basin, but rainfall was less intense at the western end of the basin. The occurrence of such extreme events is likely to account for some of the variability seen in the circulation/rainfall relationships.

No very extreme events are associated with outliers (ii) to (iv), although in each case about 20% or more of the mean seasonal rainfall falls on each day. The ratio values for these outliers were calculated by averaging over only 6, 3 and 5 rain days respectively, i.e. a small number of high rainfall events happened to occur on these particular circulation-type days within a particular sub-period. The combination of small sample size (particularly for the directional types) and the occurrence of torrential rainfall events makes it difficult to investigate the possibility of non-stationarity in circulation/rainfall relationships.

Despite the variability evident in the figures presented here, it is possible to identify consistent relationships between the circulation types and rainfall in the Agri. The relationships for Missanello are summarised in Table 5.10. Over the year as a whole, the C, HYC, E and SE-types and, to a lesser extent, the SW and W-types appear as high-rainfall types. There are, however, clear seasonal contrasts between winter and spring (when the C, HYC, E and S-types have a high probability of rainfall, which is intense in most cases), summer (when the UC, A and NE-types are associated with intense rainfall and the C, HYC, UC, NE, SE and SW-types all have a higher than average probability of rainfall) and autumn (when the directional types, from E through to NW, appear as high-rainfall types together with the C and HYC-types).

Circulation/rainfall relationships at the other stations for the non-directional types are similar to those shown in Table 5.10, but there is more spatial variability in relationships for the directional types. A final illustration of this spatial variability is provided by Figures 5.52 and 5.53, which show annual $PROP_{ct}/PROP_{tot}$ and $PREC_{ct}/PREC_{tot}$ ratios for Missanello in the centre of the basin, Moliterno at the western end and Nova Siri Scalo at the eastern end. In the case of rainfall probability (Figure 5.52), the ratios for Missanello are more similar to those of Nova Siri Scalo than Moliterno. The contrasts between the stations are greatest for rain per rain day for the directional types (Figure 5.53).

Evaluation of the relationships

Here, the extent to which the circulation type/rainfall relationships identified for the Agri can be explained by the synoptic situations underlying each circulation type (indicated by the pressure composites, Figures 5.32 to 5.35) is considered. The combined effects of direction of flow and topography have been shown to be important for the Guadalentin (Section 5.5.1). In that region, the combination of coastal ranges together with the sheltering effects of higher land to the northeast of the study region make the entire region very sensitive to the direction of flow (Romero *et al*., 1998). In the Agri, the strong east/west gradients across the basin (illustrated in Figure 5.46) reflect the orientation of the valley with respect to the Gulf of Taranto (northwesterly from the Gulf up to the confluence with the Sauro river and then westerly; Figure 5.4) and the steep gradient in altitude up the basin (Figure 5.5). Air masses associated with the E and SE-types have a track over the Mediterranean Sea (which is warmest in the east and in autumn; Meteorological Office, 1962), allowing surface and near-surface air masses to pick up moisture and heat. As these air masses move up the basin, rainfall may occur but is likely to be less intense at the western end of the basin because much of the moisture will have precipitated out further down the basin. The westernmost stations are also likely to be somewhat sheltered from E and S-type flow by the change in orientation of the basin upstream of the confluence of the Agri and Sauro river channels. In contrast, the eastern part of the basin is more sheltered than the western part from westerly and northwesterly flow (which also has a sea track) by the presence of the Apennines (Cantú, 1977).

The most consistent high-rainfall types in the Agri (i.e. in all seasons and for all stations) are the C and HYC-types, which are most frequent in winter and least frequent in summer (Figure 5.21). These types are associated with a low-pressure anomaly centred over southern Italy and a high-pressure anomaly (indicating blocking) in the Northeast Atlantic/British Isles region (Figure 5.32). The mean pressure maps for these types (Figure 5.33) indicate that the Azores High has a northeasterly orientation. This orientation of the Azores High has been associated with a tendency towards disturbed conditions in the Mediterranean (Meteorological Office, 1962). In winter and autumn, the low-pressure centre over Italy appears squeezed between the Azores High and the westwards extension of the Siberian Anticyclone. This pattern is broadly similar to one of the Mediterranean circulation regimes (Canonical Correlation Analysis pair 4) identified by Corte-Real *et al*. (1995b), which has positive SLP anomalies over the Azores and Caspian Sea with a belt of negative anomalies over the central Mediterranean, Iceland and Labrador. Corte-Real *et al*. argue that, under these conditions, moist air driven by the intensified Azores High meets the continental air masses associated with the anticyclone to the south of the Caspian Sea (an extension of the Siberian Anticyclone) and hence precipitation occurs over the Mediterranean Sea, Italy and France. They also suggest that this regime may be favourable for the formation of Mediterranean cyclones (such as Gulf of Genoa cyclones).

High-pressure blocking in the Northeast Atlantic, which is indicated by the C and HYC-type composites, is associated with more meridional circulation (Jacobeit, 1987; Moses *et al*., 1987; Maheras, 1988; Wibig, 1999) and with more frequent upper-air troughs and excursions of polar air over the Mediterranean, together with the southward displacement of the Atlantic storm tracks (Rogers, 1997). Such conditions are all conducive to wetter conditions in the western and central Mediterranean (Jacobeit, 1987; Moses *et al*., 1987; Maheras, 1988; Kutiel *et al*., 1996; Wibig, 1999).

Links between the NAO and the cyclonic (C and HYC) and anticyclonic (A and HYA) circulation types have been proposed for the Guadalentin (Sections 3.3 and 5.5.1). It was argued that the synoptic conditions underlying the Guadalentin anticyclonic (low-rainfall) types resemble the Greenland Below mode of the NAO which is associated with high positive values of the NAO index. Conversely, the synoptic conditions underlying the Guadalentin cyclonic (high-rainfall) types resemble the Greenland Above mode of the NAO. In the Agri, such relationships are less clear, although in winter both the Icelandic Low and Azores High are more intense and spatially extensive in the A and HYA-type composites than in the C and HYC-type composites (Figure 5.33a). The NAO index is negatively correlated with precipitation over a large part of southern Europe and the Mediterranean (Hurrell, 1995). Statistically significant negative correlations occur over both Spain and Italy, although the correlations are lower over Italy than over the Iberian Peninsula (Hurrell, 1995; Hurrell and van Loon, 1997). Thus stronger relationships between circulation types and the NAO are expected in the Guadalentin than in the Agri.

The central Mediterranean is not only subject to Atlantic influences, but also to complex and competing influences from southern Asia, central Africa and Siberia (Reddaway and Bigg, 1996; Wibig, 1999) together with the influence of local circulation systems including Mediterranean cyclones (Meteorological Office, 1962). Variations in the intensity and extent of the Siberian Anticyclone are evident in the pressure composites for the Agri circulation types (see below), but the other influences are not obvious.

The Siberian Anticyclone is a major feature from October through to March (Sahsamanoglou *et al*., 1991). Westward extensions of the Anticyclone (as occur in the E and SE-type pressure composites and, to a lesser extent, in the C and HYC-composites) are associated with blocking and flow across the Mediterranean from the east, northeast and southeast (Makrogiannis *et al*., 1991; Kutiel *et al*., 1996). The central pressure of the Siberian Anticyclone decreased during the 1980s, while pressure increased over the Mediterranean (Sahsamanoglou *et al*., 1991). Thus westward extensions of the Siberian Anticyclone were less frequent, the frequency of flow from the east, southeast and northeast decreased, and relatively dry conditions prevailed in the central Mediterranean (i.e. Italy, the Adriatic and Ionian Sea areas) (Maheras *et al*., 1992). Conversely, a decrease in pressure over the Mediterranean during the 1930s was associated with increased meridional flow (i.e. more frequent flow from the east, northeast and southeast) (Bardossy and Caspary, 1990) and relatively moist conditions prevailed in the central Mediterranean (Maheras *et al*., 1992).

The resolution of the circulation classification scheme developed here is coarse compared with that of Mediterranean cyclones which are likely to have an influence on the climate of the Agri. It was not, therefore, expected that individual cyclones would be identified in the classification, but is it possible to identify particular circulation types which might be conducive to cyclogenesis?

Two areas of Mediterranean cyclogenesis may affect southern Italy (Meteorological Office, 1962; Cantú, 1977; Wigley and Farmer, 1982; Alpert *et al*., 1990). The first, most active region, is the Gulf of Genoa and the second, less active region, is southern Italy. Alpert *et al*. (1990) indicate that the latter region is centred over the Gulf of Taranto (i.e. at the edge of the Agri study area), but the relatively coarse resolution of these studies (typically 2.5° x 2.5°) makes it difficult to determine the centre of activity with accuracy. Cantú (1977), quoting earlier estimates of Zenone (1959), indicates that 18% of Mediterranean winter-time cyclones develop in the Gulf of Genoa and 6.5% in the southern Italy area, compared with 22% and 3% respectively in summer. More recently, the University of Thessaloniki has developed a Mediterranean winter cyclone index for the period 1958-1997 using gridded Reanalysis data from the National Center for Environmental Prediction (ACCORD, 2000). This index gives a mean frequency of six cyclones per winter in the Gulf of Genoa and four in the southern Italy area at 00 hours, compared with means of four and two respectively at 12 hours. The lower day-time frequency of cyclogenesis is attributed to the thermal effect of the Mediterranean at night (Alpert *et al*., 1990). Similarly, Gulf of Genoa cyclones have a summer maximum, although the seasonal cycle is not as strong as for cyclogenesis in the Cyprus region, reflecting the importance of lee cyclogenesis throughout the year in the Gulf of Genoa due to the proximity of the Alps (Alpert *et al*., 1990). In spring, when land-sea contrasts are weakest, Gulf of Genoa cyclones are less frequent and cyclogenesis in the southern Italy region is not detectable in the study of Alpert *et al*. (1990).

Some Gulf of Genoa cyclones track southeast along the Tyrrhenian Sea (Meteorological Office, 1962). This track is more likely in winter: in summer, the cyclones tend to move across the Po Valley and south along the Adriatic Sea or eastwards into the Balkan region (Cantú, 1977). Cyclones following either the Tyrrhenian or Adriatic Sea track might have some influence in the Basilicata region. Urbani identified the principal large-scale circulation patterns (two for winter and two for summer) in which Mediterranean cyclogenesis is most likely to occur (Cantú, 1977).

The simplest pattern is the first winter pattern which has a low-pressure trough over central Italy, a high-pressure ridge to the west of the Iberian Peninsula associated with the Azores High and low pressure over Iceland and Scandinavia. This closely resembles the winter composite patterns for the C and HYC-types (Figure 5.33a). Thus one might speculate that Gulf of Genoa and other Mediterranean cyclones may be more likely to develop on winter days classified as C and HYC-types than on other winter days. The other three patterns identified by Urbani are more complex than the first winter pattern and it is not possible to relate them directly to any particular circulation type(s). More Gulf of Genoa cyclones might, however, also be expected on days with northerly or northwesterly flow because of the importance of Alpine lee cyclogenesis (Cantú, 1977). Investigation of the relationships between the circulation classification developed here and the occurrence of Mediterranean cyclones (using one of the newly-available cyclone catalogues such as that developed by Trigo *et al*., 1999) would be an interesting area of future work.

In general, the observed circulation/rainfall relationships in the Agri can be explained in terms of the underlying synoptic situation indicated by the pressure composites, i.e. in terms of physical mechanisms. Some relationships are less easily explained. In particular, intense rainfall occurs on summer days classified as UC, A and NE, which are low-rainfall types for the remainder of the year (Table 5.10). It is, however, possible that these are more local, convective events.

5.5.3 Discussion

In both the Guadalentin and Agri study regions it is possible to identify circulation types for which the probability of rain and/or the amount of rain per rain day is greater (or less) than average. For the most part, these relationships are supported by the underlying synoptic circulation. These surface patterns reflect the differing influences in the western and central Mediterranean. Atlantic influences are more pronounced in the Guadalentin, although easterly and southeasterly flow across the Mediterranean is also important. In the Agri, the differing seasonal influences of the Atlantic and Siberian pressure features are evident in the pressure composites but the influences of the north African and southwest Asian pressure features are not obvious. More local influences become more important moving eastwards across the Mediterranean basin, most notably in autumn when air masses tend to be unstable because of the large land-sea temperature differences (Kutiel *et al*., 1996), but are not detectable given the relatively coarse spatial resolution of the classification scheme.

Only surface patterns have been investigated here, although the importance of upper-air troughs and cut-off-lows for intense rainfall events in the Guadalentin is noted. Upper-air features are also likely to be important for southern Italy (Wibig, 1999). Thus a number of the case studies presented in Chapter 7 consider 500 hPa patterns as well as SLP patterns.

In both regions, the typing schemes are considered to be discriminating in terms of the rainfall characteristics underlying each type. This, together with the finding that each type has a characteristic underlying synoptic pattern, indicates that the schemes provide a suitable basis for downscaling. However, some types have both similar synoptic patterns and similar rainfall regimes, indicating that it may be desirable to combine them. This issue is discussed further in Chapter 6.

5.6 VALIDATION OF THE HADCM2SUL CIRCULATION TYPES

Simulated mean seasonal cycles of circulation-type frequency for the three study areas calculated from HadCM2SUL output for 1956-1989 are shown in Figure 5.21, together with the observed seasonal cycles for the same period.

As in the original scheme for the Guadalentin (Figure 2.4), the frequencies of the cyclonic types (C, HYC and UC) are consistently underestimated and the frequencies of the anticyclonic types (A, HYA and UA) are consistently overestimated in the new scheme for the Guadalentin (Figure 5.21). Similar tendencies occur to a lesser extent in the Agri and Lesvos. The largest discrepancies occur in summer, notably for the C and UC-types in the Guadalentin and the UC-type in the Agri. With these major exceptions, the shapes of the observed seasonal cycles of the non-directional types are reasonably well simulated by the model. In particular, some of the observed differences between the three regions are successfully reproduced. For example, the seasonal cycles of the A and HYA-types in the Guadalentin are correctly simulated to be stronger than in the Agri and Lesvos. In Lesvos, the model correctly reproduces the observed summer decrease in the frequency of the UC-type, and the frequency of this type correctly reaches a summer maximum in the other two regions.

The observed seasonal cycles of the majority of the directional types are reasonably well simulated, but there are a number of discrepancies. In the Guadalentin, for example, the model incorrectly simulates a second N-type maximum in May, and the E and SE-types have summer/autumn maxima although they do not have seasonal cycles in the observed data. Most of the observed seasonal cycles are reasonably well simulated for the Agri, with the exceptions of the N and SE-types. In Lesvos, the frequencies of the NE and E-types (which are both quite frequent in the observed data) are systematically underestimated, while the frequencies of a number of the other directional types (N, S, SW, W and NW) are overestimated.

The differences (in number of days) between the observed and simulated mean seasonal frequencies for the Guadalentin, Agri and Lesvos calculated over the period 1956-1989 are shown in Tables 5.11 to 5.13 respectively. Significant differences are identified using the Mann Whitney/Wilcoxon rank sum test (a non-parametric equivalent of the *t* test). In all three regions, the majority of differences are statistically significant. A number of the differences are, however, less than one day (including some of the statistically significant differences), particularly in the Agri.

A number of systematic differences (i.e. statistically significant differences of the same sign in all seasons) can be identified. In the Guadalentin, the frequency of the C-type is systematically underestimated while the frequencies of the A, HYA and S-types are systematically overestimated. In the Agri, the frequency of the UC-type is systematically underestimated while the frequencies of the A and HYA-types are systematically overestimated. In Lesvos, the frequencies of the NE and E-types are systematically underestimated while those of the A, N, S, W and NW-types are systematically overestimated.

Other differences are not consistent between seasons. In the Guadalentin, for example, the frequency of the SE-type is significantly underestimated in winter but significantly overestimated in summer and autumn. In the Agri, the frequency of the E-type is significantly underestimated in winter but significantly overestimated in spring and summer. As another example, the frequency of the C-type is significantly underestimated in Lesvos in winter and spring but significantly overestimated in autumn. In the Guadalentin and Agri, there are more statistically significant differences in summer than in other seasons. In particular, there are problems with the simulation of the C and UC-types in summer together with some of the infrequent directional types. In Lesvos, there are more statistically significant differences in spring than in other seasons.

The comparisons between observed and simulated circulation-type frequencies in Figure 5.21 and Tables 5.11 to 5.13 are based on the period 1956-1989. The climate-change scenarios developed in Chapter 6 are based on HadCM2SUL output for 1970-1979, 2030-2039 and 2090-2099. In order to determine how well the model performs during the present-day baseline period of 1970-1979, simulated mean annual and seasonal circulation-type frequencies for this period are compared with observed frequencies for the three study regions in Tables 5.14 to 5.16. Observed mean frequencies for 1970-1979 are shown in the tables together with the maximum and minimum values observed in any one (overlapping) decade during the period 1956-1989. Simulated values which are smaller than the observed minimum decadal values or larger than the observed maximum decadal values are indicated. Over the year as a whole, the simulated frequencies of the C and UC-types are lower than the minimum decadal values in all three regions, as is the frequency of the HYC-type in the Guadalentin. In contrast, the simulated frequencies of the A, HYA and N-types are higher than the maximum decadal values in all three regions. In the Guadalentin, the simulated SE and S-type frequencies are also higher than the decadal maxima. In the Agri, the simulated UA and SE-type frequencies are lower than the minimum decadal value while those for the NE and NW-types are higher than the observed maxima. Finally in Lesvos, the NE and E-type frequencies are lower than the minimum decadal values, while those of the S, SW, W and NW-types are all higher than the observed maxima.

The most serious shortcomings in the simulated circulation-type frequencies (i.e. the underestimation of the cyclonic types, particularly the UC-type in the Guadalentin and Agri in summer, and the overestimation of the anticyclonic types) are clearly related to the finding that, in all three regions, the mean value of F (the strength of flow) is overestimated by the model and the mean value of Z (total shear vorticity) is significantly lower than the observed value (i.e. smaller or more negative, indicating more anticyclonic conditions) (see discussion in Section 5.3.2). These mean values are used as new threshold values to define the UC and UA circulation types (see Section 5.3.3). The differences between observed and simulated F and Z values (see Tables 5.4 and 5.6) are smallest in Lesvos where the non-directional types are better simulated than in the other two regions (Figure 5.21). The largest difference between observed and simulated F values occurs in the Guadalentin, where the frequency of the UC-type is severely underestimated in every season except winter. The largest difference between observed and simulated Z values occurs in the Agri, but the simulation of the cyclonic (C and HYC) and anticyclonic (A and HYA) types does not appear any worse in this region than in the others (Figure 5.21).

Despite the use of new, variable threshold values, the UC-types in the Guadalentin appear to be more severely underestimated in the new classification scheme (Figure 5.21) than in the original scheme, particularly in summer and autumn (Figure 2.4). This is confirmed by Table 5.17, which shows the seasonal simulated minus observed frequencies of the eight circulation-type groups used in the original scheme for the original scheme (taken from Table 2.5) and the new scheme. The frequency of the UC-type is significantly underestimated in winter in the UKTR-based scheme, and significantly underestimated in both schemes in spring and summer (more severely so in the HadCM2SUL-based scheme). In autumn, it is significantly underestimated in the HadCM2SUL-based scheme. In part, the poorer reproduction of the UC-type in the new scheme must reflect problems with the simulated shape of the *F* and *Z* distributions in HadCM2SUL (Section 5.3.2, Figures 5.18 and 5.19) as well as the discrepancies in the mean values of these parameters. It is also likely to reflect the fact that the strength of flow decreases when the underlying pressure grid is shifted across the Iberian Peninsula (Section 5.2.3), but this relationship does not appear to be reliably reproduced inHadCM2SUL.

HadCM2SUL tends to reproduce the observed circulation types somewhat better than UKTR in winter (Table 5.17). With the exception of the A/HYA and E/NE-types, the signs of the differences are opposite for the two schemes. Whereas the frequencies of the C and HYC types are overestimated in the UKTR-based scheme, for example, they are underestimated in the HadCM2SUL-based scheme and the frequency of the A/HYA-type group is more severely overestimated. This reflects a new error which appears in winter in HadCM2SUL, i.e. positive SLP anomalies over most of the Mediterranean region (see Section 5.3.1 and Figure 5.17). In spring and summer, the differences in circulation-type frequency are larger for the HadCM2SUL scheme than for the UKTR scheme (Table 5.17). In particular, the frequencies of the cyclonic types are more severely underestimated by HadCM2SUL. With the exception of the UA-type in spring and the S/SE-type group in summer, the signs of the differences are the same in both schemes. In autumn, the differences tend to be slightly larger in the HadCM2SUL-based scheme, particularly in the case of the C and UC-types, although the frequency of the W/NW/SW/N-type group is much better simulated. With the exception of the UA-type, the signs of the differences are the same in both schemes.

The HadCM2SUL and the UKTR-based schemes are not absolutely comparable, even though the same circulation-type groups are used in Table 5.17, because different grids and threshold values are used. Also, the HadCM2SUL means are calculated over 34 years while those for UKTR are calculated over only 10 years. Overall, however, the comparison indicates that HadCM2SUL performs less well than UKTR over the Guadalentin. Thus, while SLP and atmospheric circulation are generally considered to be better simulated by HadCM2 than UKTR (Johns *et al*., 1997; Corte-Real *et al*., 1999b; see discussion in Section 5.3.1), this cannot be assumed to be true for all regions or applications. In part, this is because while links between errors in the simulated *F* and *Z* values and in circulation-type frequency are relatively easy to identify, the links between errors in the simulation of mean SLP (Section 5.3.1) and circulation-type frequency are less easy to establish.

The largest differences between observed and HadCM2SUL simulated mean SLP over the North Atlantic/European window considered here occur in winter and spring, when pressure is underestimated over a large part of the Northeast Atlantic (Figure 5.17). The cyclonic types (C and HYC) in the Guadalentin and Agri are associated with blocking in the Northeast Atlantic (see Sections 5.4.1 and 5.42). The negative pressure anomalies in the Northeast Atlantic reflect the underestimation of Atlantic blocking in the HadCM2 model (Johns *et al*., 1997) which could, in part, account for the underestimation of the frequency of the cyclonic circulation types in these two study areas. It is also possible that the underestimation of the frequency of the E-type in the Agri could be related to the underestimation of the westward extent of the Siberian Anticyclone in winter, spring and autumn (see Section 5.3.1). In general, however, it is not possible to trace the errors in mean seasonal SLP directly through to particular errors in circulation-type frequency. More significant errors in circulation-type frequency (see Tables 5.11 to 5.13) tend to occur in spring or summer than in winter when the SLP anomalies are largest (Figure 5.17). In winter, the simulated minus observed SLP anomalies over the Mediterranean are positive, whereas they are negative in other seasons (see also Table 5.3). Again, it is difficult to trace these seasonal variations in SLP error through to seasonal variations in circulation-type error, although, as illustrated earlier in this section, the sign of the circulation-type errors is sometimes different in winter than in other seasons (Tables 5.11 to 5.13).

Another problem with the simulation of SLP and *F* and *Z* parameters is that the standard deviations of their mean values are systematically overestimated (see Tables 5.3 and 5.4). Observed and simulated year-to-year standard deviations for mean circulation-type frequency are shown in Tables 5.18 to 5.20 for the three study regions. Statistically significant differences are indicated in the tables (calculated using the *F* test). Overall, there tend to be more positive differences than negative differences between the modelled minus observed circulation-type standard deviations, suggesting that the variability of the simulated circulation-type frequencies may be overestimated (as might be expected given the errors in SLP and *F* and *Z* parameters). In terms of the significant differences only, however, there tend to be more negative than positive differences, except in summer. Further inspection of the significant differences indicates that in nearly all such cases, the sign of the difference is the same for the standard deviations (Tables 5.18 to 5.20) and for mean frequency (Tables 5.11 to 5.13). The frequency and variability of the cyclonic circulation types (C, HYC and UC) tend to be underestimated, for example, while the frequency and variability of the anticyclonic circulation types (A, HYA and UA) tend to be overestimated.

A convenient parameter when differences in the mean ($\overline{X}$) affect differences in the standard deviation (σ_x) is the coefficient of variation ($\overline{X}/\sigma_x$) (von Storch and Zwiers, 1999). Observed and simulated coefficients of variation, together with the simulated minus observed differences, are shown in Tables 5.21 to 5.23 for the three study areas. No systematic differences in the coefficients of variation are evident in these tables.

The various comparisons presented in this section demonstrate that, although the HadCM2 model is considered to reproduce the main features of the circulation reasonably reliably and is considered a major improvement over UKTR (Johns *et al*., 1997; Corte-Real *et al*., 1999b), the classification scheme is very sensitive to the model shortcomings in SLP and flow parameters that still arise. It cannot be assumed that the new version of the model will be better for all regions or all applications. The potential danger of making such an assumption is illustrated by the comparison of the two schemes for the Guadalentin Basin. Except in winter, HadCM2SUL is less successful in reproducing the observed circulation-type frequencies than UKTR. It is, however, encouraging that the shapes of the seasonal cycles are reasonably well simulated by HadCM2SUL for many of the circulation types, although systematic errors in circulation-type frequency may still occur for these types. Clearly, there is a need for continuing improvements in model performance if circulation classification schemes such as those developed here are to be applied to model output with confidence. It is also clear that the discrepancies between the observed and simulated classification schemes used here are so great that it would not be realistic to construct climate-change scenarios directly by calculating differences between observed present-day values and model values for a future time period. Instead, it is necessary to calculate the difference between simulated values for a present-day time slice (here 1970-1979) and simulated values for future time slices (here 2030-2039 and 2090-2099).

5.7 FUTURE CHANGES IN HADCM2SUL CIRCULATION

5.7.1 Changes in sea level pressure

Mean seasonal SLP from HadCM2SUL is plotted for the three scenario decades (1970-1979, 2030-2039 and 2090-2099) in Figures 5.54 to 5.56 respectively. The changes between the present-day and the first future time slice (2030-2039 minus 1970-1979) are shown in Figure 5.57. The changes for the second future time slice (2090-2099 minus 1970-1979) are shown in Figure 5.58.

The pattern of change in winter with respect to 1970-1979 is broadly similar for both future time slices, with decreases in SLP over the North Atlantic to the west of the British Isles and the Iberian Peninsula and increases in SLP over the Mediterranean (Figures 5.57 and 5.58). The Mediterranean area covered by higher SLP is slightly greater in 2030-2039 than in 2090-2099 and is centred further to the west. The maximum increase is also slightly greater in 2030-2039 (+3 hPa) than in 2090-2099 (+2 hPa). In contrast, the area of lower SLP is much more extensive in 2090-2099 than in the earlier decade, and the maximum decrease is much greater (-7 hPa compared with -3 hPa). The pattern of change in autumn is broadly similar to that in winter (i.e. lower pressure over the North Atlantic and higher pressure over the Mediterranean). In this season, however, the changes are much smaller (a maximum of -5 hPa and +1 hPa in 2090-2099) and they do not vary as much in magnitude between the two future decades. In 2090-2099, the area of higher SLP in the Mediterranean is located further to the west in autumn (i.e. over central Europe) than in winter, when it is centred over Greece and western Turkey. In autumn, there is also an area of lower pressure (which is more extensive in 2030-2039 than 2090-2099) over Scandinavia and northern Russia. MSLP over the North Atlantic, but not over Scandinavia or the Arctic Ocean, is also lower in spring. The maximum fall in spring SLP is slightly greater in 2090-2099 (-4 hPa) than in 2030-2039 (-3 hPa). In summer, there are very small decreases in SLP (generally less than -1 hPa) south of about 55° N in 2030-2039 and more general, but still small decreases (a maximum of -2 hPa), over the whole North Atlantic/European window in 2090-2099.

Examination of the mean pressure maps (Figures 5.54 to 5.56) indicates that the decreases in SLP over the North Atlantic are associated with an intensification of the Icelandic Low in winter, spring and autumn and a general weakening of the Azores High in all seasons. The weakening of the Azores High is most evident in winter 2090-2099 when it no longer appears as a ridge of high pressure extending into the

Mediterranean (Figure 5.56). This weakening of the Azores High, but not the intensification of the Icelandic Low, is consistent with the trend towards weaker NAO index values in time series constructed using output from HADCM2SUL and other HADCM2 simulations (Osborn *et al*., 1999a).

The HadCM2SUL changes in SLP (Figures 5.57 and 5.58) are very different to the perturbed minus control run changes from UKTR (Figure 2.9), particularly over the North Atlantic. They also tend to be greater in magnitude, particularly in winter and autumn, and in the second decade (2090-2099). Thus the HadCM2SUL SLP changes might be expected to give rise to very different, and possibly larger, changes in circulation-type frequency compared with UKTR. The implications of these changes in SLP for changes in circulation-type frequency are discussed in the next section.

5.7.2 Changes in circulation type frequency

Mean seasonal cycles of circulation-type frequency calculated from HadCM2SUL output for 1970-1979, 2030-2039 and 2090-2099 are shown in Figures 5.59 to 5.61 for the three study regions. These seasonal cycles are calculated over 10 years and are, therefore, not as smooth as those shown in Figure 5.21 for the present-day which are calculated over 34 years. This makes it more difficult to see systematic changes in the shape of the seasonal cycles. Some examples can, however, be identified. In the Guadalentin, the frequency of the N-type decreases in the two future time-slices over the winter half of the year, so that the maximum occurs in May or June rather than in November as in the present-day time-slice. In the Agri, the seasonal cycles of the C and HYC-types, and to a lesser extent the UA-type, are weaker in 2030-2039 and 2090-2099 than in 1970-1979. In Lesvos, the seasonal cycles of some types (the UC, A, HYA and E-types) are stronger in the future time-slices, while others are weaker (the S and SW-types).

Mean seasonal changes, with respect to 1970-1979, in the frequency of the circulation types are shown in Tables 5.24 to 5.26 for the three study regions. Significant differences are indicated (** or *) using the Mann Whitney/Wilcoxon rank sum test. In all regions, there are more significant differences in 2090-2099 than in 2030-2039, as expected given the larger changes in SLP in the later decade (Section 5.7.1). In 2030-2039, fewest significant changes occur in the Agri (11 out of 56 values, i.e. 20% of all values) and most in the Guadalentin (36% of all values). In 2090-2099, fewest significant changes again occur in the Agri (23% of all values), but slightly more (46% of all values) occur in Lesvos than in the Guadalentin. Even in the first decade, proportionately more significant changes occur in the Guadalentin for HadCM2SUL (36%) than for UKTR (22%, see Table 2.6). This is not unexpected given the larger changes in SLP in HadCM2SUL (Section 5.7.1).

Tables 5.24 to 5.26 also indicate (in bold) those changes whose absolute value is greater than or equal to the absolute value of the model minus observed difference given in Tables 5.11 to 5.13. The majority, but not all, of the statistically significant changes are greater than the model errors associated with these types, even in the Guadalentin where the model errors are largest (see Section 5.6).

Differences in the year-to-year standard deviations of circulation-type frequency were also calculated for the three decades and for the three study periods and the time series tested for significant differences using the *F*-test (results not shown). Relatively few of the differences are significant at the 10% level (a minimum of 13% of all values in the Agri and Lesvos in 2030-2039 and a maximum of 23% of all values in the Agri in 2090-2099). In the majority of seasons/time-slices/regions (i.e. Guadalentin - summer and autumn, 2030-2039 and 2090-2099; Agri - spring, summer and autumn, 2030-2039; Agri - summer, 2090-2099; Lesvos - spring, summer and autumn, 2030-2039 and 2090-2099), significant changes in variance occur for only two or fewer of the circulation types. Thus it is concluded that there are no systematic changes in variance.

Very few of the changes in mean circulation-type frequency are seasonally consistent, i.e. of the same sign in all seasons. The exceptions are:

- Guadalentin, 2030-2039: S (increase), NW (decrease)
- Guadalentin, 2090-2099: SE and S (increases), N (decrease)
- Agri, 2030-2039: N and E (decreases)
- Agri, 2090-2099: HYC and N (decreases)
- Lesvos, 2030-2039: UA (increase) and C (decrease)
- Lesvos, 2090-2099: none.

In none of these cases are the changes statistically significant in all seasons.

The pattern of change is not always the same in 2030-2039 and 2090-2099. Such differences are somewhat easier to identify in Figures 5.59 to 5.61 than in Tables 5.24 to 5.26. In the Guadalentin, for example, the frequency of the UC-type decreases in August in 2030-2039 but increases in 2090-2099 and the frequency of the N-type increases in May in 2030-2039 but decreases in 2090-2099. In the Agri, the frequency of the UA-type increases in January in 2030-2039 but then decreases in 2090-2099. Such examples are less obvious in the seasonal cycles for Lesvos. From Tables 5.24 to 5.26, however, there is only one case where a significant change in 2030-2039 becomes a significant change in the opposite direction in 2090-2099: i.e. in the Guadalentin in summer, the frequency of the HYA-type increases significantly in the first decade, but then decreases significantly in the second decade.

Some consistent patterns of change can be identified. In the Agri and Lesvos in winter, the frequencies of the cyclonic circulation types (C, HYC and UC) decrease in both scenario decades and the frequencies of the anticyclonic types (A, HYA and UA) increase (with the exception of the UA-type in the Agri in 2090-2099). The majority of these changes are statistically significant (though the UC and UA-type changes tend to be less significant). This pattern of change contrasts with that in the Guadalentin in winter. In 2030-2039, the only significant change is an increase in the frequency of the HYA-type. In 2090-2099, however, there are significant increases in the frequencies of the C, HYC and UC-types and non-significant decreases in the frequencies of the A and HYA-types. The anticyclonic types in the Guadalentin are associated with an extensive Azores High covering much of the Mediterranean Basin whereas this feature is much less extensive and is tilted to the northeast in the pressure composites for the cyclonic types (Section 5.4.1). The Azores High is weaker in 2030-2039 than in 1970-1979 (Figures 5.55 and 5.57) and by 2090-2099 is hardly evident as a high pressure ridge during winter (Figures 5.56 and 5.58). Thus, the winter increase in cyclonic circulation over the Guadalentin is in agreement with the SLP changes. Over the central and eastern Mediterranean, SLP increases in winter (Figures 5.57 and 5.58), which is consistent with the increase in anticyclonic circulation types and the decrease in cyclonic circulation types in the Agri and Lesvos.

The broad pattern of SLP changes is similar in winter and autumn, but the changes are smaller in autumn (Section 5.7.1), and the pattern of cyclonic/anticyclonic circulation-type changes is less consistent than in winter. The fall in SLP in autumn over the Guadalentin is weaker than in winter and there are no significant changes in the frequencies of the cyclonic circulation types. The rise in SLP during 2090-2099 is more confined to the central Mediterranean (Figure 5.58), thus the frequencies of the anticyclonic circulation types increase over the Agri but decrease over Lesvos.

In spring and summer, SLP falls over all three study regions. The greatest decreases in these seasons are over the Guadalentin in spring during 2090-2099 but these changes are still relatively small. The SLP changes in spring and summer are not accompanied by consistent changes in the frequency of the cyclonic and anticyclonic circulation types (Tables 5.24 to 5.26). Significant decreases in the frequency of the A or HYA-types do occur (in the Guadalentin and Agri during summer, 2090-2099 and in

Lesvos in spring and summer, both decades). However, there is only one case where the frequency of the C or HYC-types increases significantly (Lesvos, summer, 2090-2099). In contrast, significant decreases in the frequencies of the C or HYC-types occur (in the Guadalentin and Lesvos in spring during 2030-2039) together with significant increases in the frequencies of the A or HYA-types (in the Guadalentin in summer during 2030-2039 and in spring during 2090-2099).

In winter, when the most consistent changes in the frequency of the non-directional circulation types occur, the C and HYC-types are identified as 'high-rainfall' types and the A, HYA and UA-types as 'low-rainfall' types in the Guadalentin (Table 5.9) and Agri (Table 5.10). The UC-type is a high-rainfall type in the Guadalentin and a low-rainfall type in the Agri during winter. The changes in these circulation types are, therefore, expected to contribute to increased rainfall in the Guadalentin and decreased rainfall in the Agri during winter, with larger changes in 2090-2099 than in 2030-2039. A similar pattern of change is also indicated in autumn. In the Guadalentin, the winter trend is likely to be reinforced by the increased frequency of the high-rainfall E, SE, S and SW-types (with the exception of the E-type in 2090-2099, the frequencies of these types increase significantly in both scenario decades). The E and SE-types are also high-rainfall types in winter for Missanello in the Agri. The frequency of the E-type decreases while that of the SE-type increases (significantly so in 2090-2099). The latter change could partially offset the decrease in rainfall due to the other circulation-type changes.

There tend to be more significant circulation-type frequency changes in the Guadalentin and Agri in winter, and the changes are more consistent, than in other seasons. Thus it is possible to identify the patterns of rainfall change which might be expected in winter and, with less certainty, in autumn. It is not, however, possible to determine the balance of the circulation-type changes and hence the expected pattern of rainfall change in spring and summer. To do this, and to quantify the changes in winter and autumn, a conditional weather generator is required, as described in the next chapter.

5.8 SUMMARY OF CONCLUSIONS

- The transferability of the downscaling method is further tested by applying it to a new region, the Agri, in the central Mediterranean. In addition, a more recent version of the GCM, HadCM2SUL, is used.

- A method of identifying more appropriate threshold values for the unclassified circulation types is developed. It produces a more balanced typing scheme and reduces the impact of the GCM errors.
- The new typing scheme is shown to give circulation types for the Guadalentin and Agri study areas which have characteristic and physically distinct synoptic patterns and are discriminating in terms of the rainfall characteristics associated with each type. The scheme successfully reflects the different large-scale circulation influences in the two regions and the observed spatial variability in the Agri.
- HadCM2SUL has some success in reproducing the observed circulation types, although systematic errors still occur. For the Guadalentin, performance tends to be worse for HadCM2SUL than for UKTR, except in winter.
- Future changes in sea level pressure and circulation-type frequency are larger for HadCM2SUL than for UKTR and the patterns of change are different. In winter and autumn, the HadCM2SUL changes in circulation-type frequency are clearly larger than the GCM errors.

Table 5.1: Details of the eleven Agri stations. Means are calculated over the full period of record for each station.

	Altitude (m)	*Latitude Longitude*	*Annual number of rain days*	*Annual rainfall (mm)*	*Period of record*
Aliano	497	40.3N 16.2E	83	748	1951-1992
Corleto Perticara	746	40.4N 16.0E	126	803	1951-1977
Missanello	566	40.3N 16.3E	88	804	1951-1992
Moliterno	879	40.2N 15.9E	137	1134	1951-1978
Nova Siri Scalo	2	40.1N 16.6E	95	550	1951-1990
Pisticci	364	40.4N 16.6E	90	604	1951-1992
Roccanova	654	40.2N 16.2E	88	725	1951-1992
Senise	330	40.2N 16.3E	122	744	1951-1988
San Martino d'Agri	661	40.2N 16.1E	99	791	1951-1992
Stigliano	909	40.4N 16.2E	87	811	1951-1977
Tursi	348	40.3N 16.5E	90	730	1951-1992

Table 5.2: Mean observed values of *F* and *Z* (absolute values) and percentage of days on which *F/Z* thresholds of <4 and <6 are exceeded, calculated for four grids using observed data for 1956-1989. nc = not calculated.

Grid	*F*	*abs Z*	*% days F/Z <4*	*% days F/Z <6*
HadCM2-GRID$_{5\cdot 63W}$	5.5	4.7	nc	45
HadCM2-GRID$_{1\cdot 88W}$	4.8	4.2	31	56
HadCM2-GRID$_{16\cdot 88E}$	4.6	4.2	37	63
HadCM2-GRID$_{28\cdot 13E}$	5.3	4.2	25	52

Table 5.3: Comparison of observed ($_{obs}$) and HadCM2SUL simulated ($_{sim}$) SLP means and standard deviations (σ) calculated over 32 grid points for the three study regions for 1956-1989. Differences which are significant at the 5% level (calculated using the *t* test for means) or 10% level (calculated using the *F* test for standard deviations) are indicated (*).

	Guadalentin	*Agri*	*Lesvos*
Winter			
$Mean_{obs}$	1019.11	1016.87	1017.10
$Mean_{sim}$	1020.02*	1017.88*	1017.10
σ_{obs}	7.96	7.37	6.35
σ_{sim}	8.39*	7.49	6.65*
Spring			
$Mean_{obs}$	1016.18	1014.27	1013.87
$Mean_{sim}$	1015.12*	1013.15*	1012.60*
σ_{obs}	5.33	4.66	4.37
σ_{sim}	7.00*	6.00*	5.48*
Summer			
$Mean_{obs}$	1017.14	1014.20	1011.51
$Mean_{sim}$	1016.10*	1013.17*	1010.19*
σ_{obs}	2.70	2.67	2.77
σ_{sim}	3.97*	3.87*	3.82*
Autumn			
$Mean_{obs}$	1018.02	1017.21	1016.80
$Mean_{sim}$	1017.81	1016.48*	1015.69*
σ_{obs}	5.09	4.77	4.26
σ_{sim}	5.87*	5.52*	4.94*

Table 5.4: Comparison of observed ($_{obs}$) and HadCM2SUL simulated ($_{sim}$) resultant flow (*F*) and total shear vorticity (*Z*) means and standard deviations (σ) for the three study regions for the period 1956-1989. Differences which are significant at the 5% level (calculated using the *t* test for means) or 10% level (calculated using the *F* test for standard deviations) are indicated (*). Guad. = Guadalentin.

	Guad. F	*Guad. Z*	*Agri F*	*Agri Z*	*Lesvos F*	*Lesvos Z*
Winter						
$Mean_{obs}$	6.61	-1.57	6.13	4.27	6.74	-0.30
$Mean_{sim}$	6.89*	-4.10*	6.92*	2.19*	6.71	-1.88*
σ_{obs}	3.82	6.40	3.63	7.24	3.85	6.94
σ_{sim}	3.99*	6.44	3.77*	8.21*	4.01*	7.81*
Spring						
$Mean_{obs}$	4.89	1.05	4.59	1.67	4.82	0.27
$Mean_{sim}$	6.71*	-1.81*	6.16*	0.98*	5.64*	-1.30*
σ_{obs}	2.86	5.33	2.89	5.62	2.95	5.26
σ_{sim}	3.57*	6.55*	3.58*	7.37*	3.22*	6.76*
Summer						
$Mean_{obs}$	3.07	2.27	3.29	0.88	4.43	-1.20
$Mean_{sim}$	5.92*	-1.06*	4.56*	-0.74*	4.72*	-2.18*
σ_{obs}	1.69	3.56	1.82	3.36	2.17	3.99
σ_{sim}	2.73*	5.79*	2.39*	5.46*	2.55*	5.17*
Autumn						
$Mean_{obs}$	4.60	-0.30	4.35	1.83	5.16	-1.69
$Mean_{sim}$	6.05*	-2.17*	5.61*	0.68*	5.22	-2.66*
σ_{obs}	3.02	5.16	2.90	5.19	2.90	4.69
σ_{sim}	3.20*	5.79*	3.17*	6.95*	3.18*	5.61*

Table 5.5: Mean values of *F* and *Z* (absolute values) and percentage of days on which *F/Z* thresholds of <4 and <6 are exceeded, calculated for three grids using HadCM2SUL output for 1956-1989.

Grid	*F*	*abs Z*	*% days F/Z <4*	*% days F/Z <6*
HadCM2-GRID$_{1 \cdot 88W}$	6.4	5.5	9	28
HadCM2-GRID$_{16 \cdot 88E}$	5.8	5.6	14	39
HadCM2-GRID$_{28 \cdot 13E}$	5.6	5.4	17	39

Table 5.6: Mean values of observed and simulated resultant flow (*F*) and total shear vorticity (*Z*, mean of absolute values), for the period 1956-1989, used as thresholds in the new circulation classification scheme.

	Guadalentin	*Agri*	*Lesvos*
Observed F	4.8	4.6	5.3
Simulated F	6.4	5.8	5.6
Observed Z	4.2	4.2	4.2
Simulated Z	5.5	5.6	5.4

Table 5.7: Percentage of days classified as UC or UA using *F/Z* threshold values of 6.0, 4.0 and observed/simulated mean values (see Table 5.6) for the three study regions for the period 1956-1989. Guad. = Guadalentin.

	Guad.			*Agri*			*Lesvos*		
	F/Z < *6.0*	*F/Z* < *4.0*	*F/Z* < *mean*	*F/Z* < *6.0*	*F/Z* < *4.0*	*F/Z* < *mean*	*F/Z* < *6.0*	*F/Z* < *4.0*	*F/Z* < *mean*
Winter									
Obs.	31	12	16	40	18	23	32	15	21
Sim.	19	6	19	27	9	25	23	8	19
Spring									
Obs.	55	28	35	60	31	38	57	29	41
Sim.	25	9	26	34	12	31	36	14	30
Summer									
Obs.	81	50	60	86	56	65	65	30	46
Sim.	35	10	36	53	22	49	54	27	47
Autumn									
Obs.	59	33	40	66	40	47	54	26	38
Sim.	34	11	34	39	15	36	42	19	36

Table 5.8: Mean annual and seasonal frequencies (days) of the 14 circulation types for the three study regions calculated from the observed data, 1956-1989.

GUADALENTIN	*Annual*	*Winter*	*Spring*	*Summer*	*Autumn*
C	30.7	3.4	7.9	14.5	5.0
HYC	28.1	4.6	9.1	9.5	5.1
UC	76.3	3.9	15.6	38.6	18.4
A	24.1	11.3	3.5	1.3	8.2
HYA	29.6	12.5	7.1	1.0	8.8
UA	62.4	10.2	16.7	16.9	18.6
N	35.8	14.9	9.9	2.3	8.6
NE	16.1	6.1	4.5	2.0	3.3
E	5.8	1.2	1.6	1.2	2.0
SE	5.8	1.6	1.7	1.0	1.4
S	8.0	1.9	2.8	1.3	2.1
SW	9.5	3.9	2.6	0.2	2.8
W	11.0	4.9	3.4	0.5	2.1
NW	21.5	9.8	5.8	1.5	4.8
AGRI	*Annual*	*Winter*	*Spring*	*Summer*	*Autumn*
C	37.6	14.1	9.7	5.3	8.5
HYC	36.9	13.5	8.7	5.7	8.9
UC	72.6	9.7	14.8	29.7	18.3
A	10.6	1.8	4.3	2.3	2.2
HYA	11.0	2.7	4.0	1.0	3.4
UA	85.4	9.7	20.3	30.9	24.6
N	21.9	3.5	5.8	10.1	2.5
NE	13.5	5.2	2.6	2.4	3.3
E	7.3	3.3	1.0	0.0	3.0
SE	15.7	7.7	3.2	0.2	4.6
S	23.0	9.3	7.1	0.7	6.2
SW	13.1	4.6	3.8	0.6	4.1
W	7.7	2.8	3.1	0.5	1.2
NW	9.1	2.0	3.7	2.7	0.6
LESVOS	*Annual*	*Winter*	*Spring*	*Summer*	*Autumn*
C	20.4	6.3	7.8	3.4	2.9
HYC	19.3	6.9	6.3	3.2	2.7
UC	54.4	6.9	17.3	17.2	13.0
A	23.0	6.2	4.8	5.2	6.9
HYA	38.0	10.5	6.9	10.1	10.8
UA	77.0	11.3	20.6	23.7	21.4
N	9.9	3.0	2.6	2.6	1.5
NE	57.3	13.6	11.2	18.9	13.7
E	32.5	8.1	5.4	7.3	11.9
SE	4.7	2.4	1.4	0.1	0.6
S	8.0	4.4	2.1	0.0	1.6
SW	16.1	8.5	4.0	0.1	3.5
W	2.9	1.4	1.1	0.0	0.2
NW	1.1	0.3	0.6	0.1	0.1

Table 5.9: High-rainfall circulation types with a higher than average proportion of wet days at every station (+) and a higher than average amount of rain per rain day at every station (*) or at five stations (x) in the Guadalentin.
Low-rainfall circulation types with a lower than average proportion of wet days at every station (-) and a lower than average amount of rain per rain day at every station (*) or at five stations (x) in the Guadalentin.

	C	*HYC*	*UC*	*A*	*HYA*	*UA*	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*
High rainfall														
Annual	+	+*						+	+*	+*	+			
Winter	+	+	+					x	+*	+*	+	+		
Spring	+x	+							+*	+x				
Summer	+	+*							+	+				
Autumn	+	+						+	+*	+*	+			
Low rainfall														
Annual			-	-*	-x	-x	-*				*	*	-*	-*
Winter				-x	-x	-	-					*	*	-*
Spring				-x	-*	-x	-x	*			*	*	-x	-x
Summer	x		-*	-*	-*	-	*			x		-*	-*	-*
Autumn	*			-*	-	-	-*				*			-x

Table 5.10: High-rainfall circulation types with a higher than average proportion of wet days at Missanello (+) and a higher than average amount of rain per rain day at Missanello (*).
Low-rainfall circulation types with a lower than average proportion of wet days at Missanello (-) and a lower than average amount of rain per rain day at Missanello (*).

	C	*HYC*	*UC*	*A*	*HYA*	*UA*	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*
High rainfall														
Annual	+*	+*							+*	+*		+	+	
Winter	+	+*							+	+*				
Spring	+*	+*							+*	+*				
Summer	+	+	+*	*				+*		+		+		
Autumn	+*	+*							*	+*	+*	+	+	+*
Low rainfall														
Annual			-*	-*	-*	-*	-*	*				*	*	-
Winter			-*	-*	-*	-*	-*	-*			*	*	*	-*
Spring				-*	-*	-*	*	*			-*		*	-*
Summer		*		-		-	*			*	-*	*	-*	-
Autumn			-*	-*	-*	-*	*	*						

Table 5.11: Differences (simulated minus observed days) between observed and HadCM2SUL mean circulation-type frequencies for the Guadalentin over the period 1956-1989. Differences which are significant at the 5% (**) or 10% (*) level are indicated (calculated using the Mann Whitney/Wilcoxon rank sum test).

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	-1.7*	-4.7**	-8.9**	-2.6**
HYC	-0.7	-4.0**	-3.0**	-0.5
UC	+0.2	-7.0**	-23.2**	-5.0**
A	+3.5**	+6.2**	+6.2**	+1.8**
HYA	+3.9**	+5.0**	+8.7**	+4.3**
UA	+2.6**	-1.5	+1.2*	-1.6
N	-4.5**	+3.6**	+4.4**	+1.4
NE	-4.3**	-2.6**	+3.9**	-0.8
E	-0.6	-0.5	+2.0**	-1.8
SE	-1.4*	+0.2	+6.1**	+2.9**
S	+2.8**	+1.9**	+2.7**	+3.9**
SW	+2.0**	+0.3	0.0	-0.7
W	-0.2	+0.4	0.0	-0.7
NW	-1.5	+2.9**	-0.2*	-0.6

Table 5.12: Differences (simulated minus observed days) between observed and HadCM2SUL mean circulation-type frequencies for the Agri over the period 1956-1989. Differences which are significant at the 5% (**) or 10% (*) level are indicated (calculated using the Mann Whitney/Wilcoxon rank sum test).

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	-5.8**	-1.7*	-2.3**	+0.5
HYC	-0.4	+0.8	+0.8	-0.6
UC	-1.5*	-3.6**	-12.3**	-4.6**
A	+4.1**	+3.3**	+8.6**	+5.2**
HYA	+2.4**	+1.7**	+4.8**	+2.7**
UA	+3.4**	-3.6**	-2.8**	-5.1**
N	+4.7**	+0.5	-2.3**	+2.2**
NE	-0.7	+1.0**	+0.2	+1.6**
E	-2.1**	+0.6**	+0.2**	-0.2
SE	-5.8**	+0.1	+0.7**	-2.7
S	-0.3	+0.6	+1.1**	+1.8**
SW	-0.2	-0.1	+0.7**	-0.2
W	-0.5	+0.2	+1.0**	-0.9
NW	+2.4**	+0.2	+1.6**	+0.3**

Table 5.13: Differences (simulated minus observed days) between observed and HadCM2SUL mean circulation-type frequencies for Lesvos over the period 1956-1989. Differences which are significant at the 5% (**) or 10% (*) level are indicated (calculated using the Mann Whitney/Wilcoxon rank sum test).

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	-2.1*	-1.7**	-0.8	+0.5*
HYC	-1.6	-0.7	-1.0	+0.7**
UC	-1.9**	-5.7**	-1.1	-2.3
A	+7.3**	+7.8**	+4.5**	+6.6**
HYA	+2.8*	+2.6**	+1.8*	+1.3
UA	+1.0	-5.2**	+1.8	+0.1
N	+2.9**	+2.2**	+0.9**	+1.8**
NE	-11.4**	-5.9**	-8.2**	-5.0**
E	-5.9**	-3.7**	-2.1*	-8.5**
SE	-0.4	+0.7**	+0.3**	0.0
S	+2.8**	+3.9**	+0.4**	+3.3**
SW	+2.6**	+2.7**	+1.2**	+0.6
W	+1.3**	+1.6**	+1.2**	+0.5**
NW	+2.5**	+1.4**	+1.1**	+0.6**

Table 5.14: Mean annual and seasonal frequencies (%) of the 14 circulation types for the Guadalentin study region calculated from the observations (maximum and minimum decadal values, mean for 1970-1979) and HadCM2SUL output (mean for 1970-1979). Simulated values which are smaller than the observed minimum decadal value (-) or larger than the observed maximum decadal value (+) are indicated in the last row (difference).

	C	*HYC*	*UC*	*A*	*HYA*	*UA*	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*
YEAR														
Decadal max	10.0	8.6	23.4	8.3	9.2	18.8	10.9	5.4	2.4	2.0	2.9	3.9	4.3	6.8
Decadal min	6.3	6.1	18.1	5.7	6.8	15.1	8.3	3.4	0.9	1.1	1.7	2.0	2.4	5.0
Obs. 1970-79	8.7	8.3	21.8	6.4	7.6	17.5	9.4	4.9	1.4	1.4	1.8	2.4	2.5	5.8
GCM 1970-79	3.8	5.4	10.9	11.2	13.8	17.6	12.0	4.6	2.0	4.1	4.7	2.4	2.4	5.1
Difference	-	-	-	+	+		+			+	+			
WINTER														
Decadal max	4.4	6.3	4.8	15.0	15.2	14.6	19.7	9.3	1.8	2.0	2.5	5.4	7.6	13.4
Decadal min	2.0	3.7	3.6	11.3	12.9	8.5	13.6	5.4	1.0	1.1	1.2	3.1	4.0	8.6
Obs. 1970-79	3.5	5.6	4.5	12.5	14.1	13.6	13.6	8.4	1.5	1.5	2.0	4.0	5.3	9.8
GCM 1970-79	2.3	3.9	4.2	16.7	17.1	14.2	14.3	2.8	0.3	1.1	4.2	5.6	5.1	8.1
Difference				+	+			-	-		+	+		-
SPRING														
Decadal max	11.6	11.9	19.6	5.6	9.3	21.8	12.8	6.5	2.9	2.9	4.2	4.4	5.5	8.2
Decadal min	5.1	5.8	14.0	2.8	5.4	15.4	7.1	3.5	1.1	1.0	2.3	2.2	2.1	4.7
Obs. 1970-79	10.9	11.3	17.9	3.8	5.5	17.2	12.0	4.0	1.3	2.2	2.3	2.6	2.4	6.6
GCM 1970-79	5.9	5.0	10.7	10.4	12.3	18.9	13.1	2.0	1.3	2.2	6.2	2.7	2.3	6.9
Difference		-	-	+	+		+	-			+			
SUMMER														
Decadal max	21.2	11.6	47.1	2.9	2.2	22.7	3.6	3.1	3.1	1.6	3.1	0.5	0.6	2.3
Decadal min	10.9	9.1	36.7	0.5	0.3	15.2	1.2	1.5	0.4	0.6	1.1	0.0	0.1	0.7
Obs. 1970-79	14.7	10.4	47.1	0.6	0.9	17.3	1.7	2.2	0.7	0.6	1.1	0.2	0.4	2.1
GCM 1970-79	4.7	7.7	16.0	7.3	10.4	19.1	9.0	7.8	4.3	7.4	4.0	0.7	0.3	1.2
Difference	-	-	-	+	+		+	+	+	+	+	+		
AUTUMN														
Decadal max	6.7	6.5	27.7	12.1	12.1	22.5	13.2	5.1	3.5	3.1	3.5	5.4	3.9	7.1
Decadal min	5.0	4.1	13.9	6.3	8.0	18.4	6.5	2.2	0.4	0.2	1.5	1.8	1.5	4.2
Obs. 1970-79	5.5	6.3	17.3	9.0	9.9	21.8	10.8	4.8	2.7	1.6	1.5	2.1	2.0	4.6
GCM 1970-79	2.3	4.9	12.7	10.4	15.4	18.1	11.6	5.7	1.9	5.7	4.3	0.9	1.8	4.3
Difference	-		-		+	-		+		+	+	-		

Table 5.15: Mean annual and seasonal frequencies (%) of the 14 circulation types for the Agri study region calculated from the observations (maximum and minimum decadal values, mean for 1970-1979) and HadCM2SUL output (mean for 1970-1979). Simulated values which are smaller than the observed minimum decadal value (-) or larger than the observed maximum decadal value (+) are indicated in the last row (difference).

	C	*HYC*	*UC*	*A*	*HYA*	*UA*	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*
YEAR														
Decadal max	11.2	11.0	20.9	4.5	4.0	24.8	7.2	4.2	2.3	4.8	7.2	4.6	2.9	2.9
Decadal min	9.6	9.6	19.1	2.3	2.6	21.1	5.6	3.2	1.5	3.0	5.5	3.0	1.5	2.2
Obs. 1970-79	10.2	10.2	20.2	2.3	2.8	23.6	6.1	3.4	2.1	4.6	7.1	3.3	1.8	2.5
GCM 1970-79	6.9	9.8	14.4	8.6	6.3	21.0	7.6	5.1	1.7	3.0	6.6	3.4	2.1	3.5
Difference	-		-	+	+	-	+	+		-				+
WINTER														
Decadal max	23.3	17.0	12.0	3.0	3.5	12.4	4.8	6.9	4.4	12.0	12.5	6.9	3.9	2.9
Decadal min	11.1	13.9	10.0	1.0	2.5	9.1	3.2	3.8	2.6	4.3	8.5	3.5	1.7	1.4
Obs. 1970-79	11.1	15.1	11.5	2.4	3.5	11.3	4.0	4.1	4.4	12.0	12.1	4.1	2.1	2.1
GCM 1970-79	10.7	14.4	9.7	5.6	5.2	12.9	8.0	7.6	2.6	2.4	7.9	5.3	3.3	4.4
Difference	-		-	+	+	+	+	+	-	-	-			+
SPRING														
Decadal max	12.1	12.4	18.3	6.2	5.5	24.6	8.4	3.5	1.5	4.6	8.9	5.3	5.1	4.4
Decadal min	9.2	7.8	13.2	3.0	3.8	17.8	5.5	1.8	0.3	2.1	5.8	3.7	1.9	3.5
Obs. 1970-79	11.4	9.0	16.9	3.6	4.3	22.1	6.2	2.3	1.3	3.4	8.4	4.3	2.3	4.4
GCM 1970-79	5.3	8.1	12.4	9.3	8.1	20.2	8.3	3.8	1.8	4.9	8.2	2.8	2.2	4.4
Difference	-		-	+	+			+	+	+		-		+
SUMMER														
Decadal max	7.3	8.3	36.0	4.9	1.8	35.8	12.9	3.2	0.0	0.5	1.1	1.3	0.7	4.4
Decadal min	3.8	4.4	29.6	1.2	0.7	27.6	9.7	1.8	0.0	0.0	0.5	0.4	0.4	1.8
Obs. 1970-79	6.2	7.2	34.3	1.5	0.7	32.7	10.7	2.1	0.0	0.1	1.0	0.6	0.4	2.4
GCM 1970-79	3.4	8.1	19.6	11.9	5.9	29.6	8.3	3.2	0.2	1.2	1.8	1.2	2.0	3.6
Difference	-		-	+	+		-	+	+	+	+		+	
AUTUMN														
Decadal max	11.7	10.4	23.8	3.9	5.0	29.0	4.0	5.3	4.3	6.5	8.2	6.4	1.9	1.1
Decadal min	6.5	8.8	17.8	1.7	2.6	24.6	1.9	1.7	2.0	2.4	5.7	3.5	0.5	0.2
Obs. 1970-79	11.3	9.5	17.8	2.0	3.2	27.9	3.1	5.3	3.0	3.6	6.7	3.7	1.9	1.0
GCM 1970-79	8.3	8.6	15.8	7.6	6.1	21.3	5.8	5.7	2.2	3.3	8.4	4.4	0.8	1.7
Difference		-	-	+	+	-	+	+			+			+

Table 5.16: Mean annual and seasonal frequencies (%) of the 14 circulation types for the Lesvos study region calculated from the observations (maximum and minimum decadal values, mean for 1970-1979) and HadCM2SUL output (mean for 1970-1979). Simulated values which are smaller than the observed minimum decadal value (-) or larger than the observed maximum decadal value (+) are indicated in the last row (difference).

	C	*HYC*	*UC*	*A*	*HYA*	*UA*	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*
YEAR														
Decadal max	6.5	5.7	17.9	7.2	11.4	22.0	4.2	16.5	10.5	1.5	2.9	5.0	0.9	0.4
Decadal min	5.4	4.6	13.6	4.5	9.6	20.4	1.6	13.5	6.1	1.0	1.6	4.1	0.5	0.2
Obs. 1970-79	5.4	5.2	14.0	6.9	10.2	20.9	2.9	16.5	8.9	1.2	2.4	4.5	0.7	0.3
GCM 1970-79	5.3	4.9	12.6	12.6	12.3	20.4	4.7	7.9	3.1	1.3	4.8	5.9	1.8	2.3
Difference	-		-	+	+		+	-	-		+	+	+	+
WINTER														
Decadal max	10.9	9.7	9.8	8.0	13.3	15.0	5.0	16.6	13.0	3.7	8.5	11.5	2.2	0.7
Decadal min	4.9	6.4	5.4	6.3	8.5	9.6	2.7	13.0	3.7	2.5	2.5	7.3	0.6	0.0
Obs. 1970-79	4.9	6.4	5.8	8.0	12.4	15.0	3.4	16.1	11.8	3.1	4.1	7.6	1.3	0.1
GCM 1970-79	7.0	7.0	6.0	12.8	12.9	13.3	6.4	4.3	1.9	0.9	9.1	12.0	2.6	3.8
Difference				+			+	-	-	-	+	+	+	+
SPRING														
Decadal max	9.2	8.5	23.0	6.8	9.5	25.8	4.0	15.3	6.8	1.8	3.0	5.8	1.6	1.1
Decadal min	6.4	5.5	14.7	3.8	6.6	19.0	1.7	9.9	4.5	0.8	1.5	3.4	0.5	0.4
Obs. 1970-79	8.6	6.8	20.8	6.7	7.7	20.6	3.3	9.9	5.4	1.1	2.7	4.5	1.0	1.1
GCM 1970-79	6.3	5.8	13.3	11.8	13.0	18.1	5.6	6.3	2.4	2.8	4.6	4.4	2.6	3.0
Difference	-		-	+	+	-	+	-	-	+	+		+	+
SUMMER														
Decadal max	4.1	4.1	22.5	7.0	15.1	27.8	4.7	22.5	9.4	0.2	0.1	0.2	0.2	0.2
Decadal min	3.3	2.7	16.7	3.3	8.8	24.5	1.1	14.9	6.5	0.0	0.0	0.0	0.0	0.0
Obs. 1970-79	3.7	3.8	17.2	5.4	10.6	26.3	3.3	22.2	7.3	0.1	0.0	0.1	0.0	0.0
GCM 1970-79	3.7	3.7	19.3	11.1	9.8	28.0	2.1	12.2	5.2	0.6	0.4	1.2	1.2	1.4
Difference				+		+		-	-	+	+	+	+	+
AUTUMN														
Decadal max	4.2	4.1	18.8	9.7	14.2	25.5	3.0	18.1	15.2	1.1	2.6	5.4	0.5	0.2
Decadal min	2.8	2.7	12.0	5.2	9.3	21.2	0.8	8.9	9.5	0.0	1.3	2.9	0.0	0.0
Obs. 1970-79	4.2	3.6	12.0	7.6	10.3	21.4	2.0	18.1	12.5	0.6	2.5	4.7	0.4	0.1
GCM 1970-79	4.2	3.0	11.7	14.8	13.7	22.3	4.7	8.8	2.8	1.1	5.2	5.8	0.9	1.1
Difference			-	+			+	-	-		+	+	+	+

Table 5.17: Differences (simulated minus observed (days)) between observed (1956-1989) and UKTR (Years 66 to 75) and HadCM2SUL (1956-1989) simulated circulation-type frequencies. Differences which are significant at the 5% level are indicated (**).

	C	*HYC*	*UC*	*A/HYA*	*UA*	*W/NW/SW/N*	*E/NE*	*S/SE*
Winter								
UKTR	+2**	+1	-2**	+3	-9**	+14**	-6**	-2**
HadCM2SUL	-2	-1	0	+7**	+3**	-4	-5**	+1
Spring								
UKTR	-3	-1	-9**	+12**	+2	+4	-6**	+1
HadCM2SUL	-5**	-4**	-7**	+11**	-2	+7**	-3**	+2**
Summer								
UKTR	-5**	-1	-15**	+8**	+6**	<1	+8**	-1
HadCM2SUL	-9**	-3**	-23**	+15**	+1	+4**	+6**	+9**
Autumn								
UKTR	0	<1	-1	+6**	+2	-10**	-1	+4**
HadCM2SUL	-3**	0	-5**	+6**	-2	-1	-3	+7**

Table 5.18: Observed (*obs*) and simulated (*sim*) (HadCM2SUL) standard deviations of mean seasonal circulation-type frequency over the period 1956-1989 for the Guadalentin. Simulated values which are significantly different (calculated using the *F*-test) from the observed values at the 5% (**) or 10% (*) level are indicated.

Type	*Winter obs*	*Winter sim*	*Spring obs*	*Spring sim*	*Summer obs*	*Summer sim*	*Autumn obs*	*Autumn sim*
C	2.4	1.1**	3.4	3.1**	7.2	2.6**	3.2	2.7
HYC	2.5	1.7	3.1	2.5**	4.0	3.1*	3.0	2.7
UC	2.1	2.8	4.8	3.0**	8.0	4.5**	7.1	4.7**
A	4.7	5.5	2.0	3.2	2.1	4.1**	4.1	3.6
HYA	3.3	4.4**	2.2	3.7	2.0	3.4**	3.9	4.1
UA	5.0	4.2*	4.0	5.0**	5.5	5.2**	5.5	5.1**
N	6.3	7.3	4.1	4.7	2.6	4.7**	5.3	4.7
NE	4.0	1.6**	2.8	2.1**	2.1	2.7	3.4	2.4*
E	1.1	1.1	1.4	1.1**	2.4	2.2	3.5	2.0**
SE	1.9	1.1**	1.7	2.3	0.9	3.8**	2.2	2.9**
S	1.6	4.2**	1.8	2.3	1.5	2.6	0.4	3.5**
SW	2.1	2.9	1.7	2.3	0.5	0.8**	2.8	1.9**
W	2.5	2.8	2.2	2.9	0.4	0.5**	1.4	1.3
NW	3.3	3.9	2.8	4.3	2.3	1.8**	2.7	2.6

Table 5.19: Observed (*obs*) and simulated (*sim*) (HadCM2SUL) standard deviations of mean seasonal circulation-type frequency over the period 1956-1989 for the Agri. Simulated values which are significantly different (calculated using the *F*-test) from the observed values at the 5% (**) or 10% (*) level are indicated.

Type	*Winter obs*	*Winter sim*	*Spring obs*	*Spring sim*	*Summer obs*	*Summer sim*	*Autumn obs*	*Autumn sim*
C	7.1	5.2**	3.3	3.4**	2.4	2.3	3.2	3.9*
HYC	4.2	3.6**	3.7	4.1	2.8	3.2	2.4	4.3
UC	2.7	2.6**	5.3	3.7**	6.7	5.0**	6.4	3.9**
A	2.1	2.9	3.2	3.7	2.6	5.0**	1.9	3.3
HYA	1.6	3.7**	2.5	3.2	1.4	3.3**	1.9	3.1
UA	5.3	4.5	5.7	4.2**	5.0	6.3**	4.8	5.2**
N	1.5	2.5*	3.4	3.5	3.1	3.7**	1.9	2.5
NE	3.0	3.8	2.2	2.7**	1.4	2.4	2.8	3.5**
E	2.1	2.0	1.2	1.6	-	-	2.7	3.5
SE	5.6	2.7**	2.2	2.7	0.4	1.1	6.8	3.7**
S	3.0	3.4	2.8	3.1	0.9	2.1**	2.8	3.3
SW	2.2	2.6	1.8	1.7	0.8	1.4	2.3	2.5
W	2.0	2.8	1.5	2.1	0.6	1.7	1.6	0.8**
NW	1.1	2.0**	1.7	2.7	2.1	2.7	0.8	1.3

Table 5.20: Observed (*obs*) and simulated (*sim*) (HadCM2SUL) standard deviations of mean seasonal circulation-type frequency over the period 1956-1989 for Lesvos. Simulated values which are significantly different (calculated using the *F*-test) from the observed values at the 5% (**) or 10% (*) level are indicated.

Type	*Winter obs*	*Winter sim*	*Spring obs*	*Spring sim*	*Summer obs*	*Summer sim*	*Autumn obs*	*Autumn sim*
C	3.0	2.3**	2.9	2.4**	1.1	2.1	1.7	1.8
HYC	3.4	3.0	2.5	2.5*	2.5	1.8**	1.4	1.9
UC	2.7	2.3**	5.4	3.1**	7.0	4.9**	4.3	3.8**
A	2.4	4.9	2.4	3.3	3.3	3.2	4.4	4.1
HYA	4.9	3.9	2.3	3.7	6.0	4.3**	5.2	3.7
UA	3.6	2.9**	5.1	3.9**	5.7	7.2**	4.0	4.6**
N	2.2	2.2	2.0	2.6	2.9	2.7	2.0	2.6
NE	3.9	1.6**	5.0	3.3**	5.7	4.6**	6.5	5.1
E	4.5	1.6**	3.5	1.6**	4.1	3.1	6.1	3.5**
SE	1.2	1.0	1.5	1.5	0.2	0.6**	1.1	1.1**
S	2.6	4.7	1.2	2.5**	-	-	0.9	3.0**
SW	3.7	4.7	1.9	3.2*	0.4	1.4**	2.6	2.5
W	1.4	2.7**	1.1	2.4**	0.2	1.6**	0.8	1.0
NW	0.8	1.7**	1.2	1.9**	0.4	1.1**	0.4	1.0**

Table 5.21: Observed (*obs*) and simulated (*sim*) (HadCM2SUL) coefficients of variation, and simulated minus observed difference, of mean seasonal circulation-type frequency over the period 1956-1989 for the Guadalentin.

	Win. obs.	*Win. sim.*	*Win. diff.*	*Spr. obs.*	*Spr. sim.*	*Spr. diff.*	*Sum. obs.*	*Sum. sim.*	*Sum. diff.*	*Aut. obs.*	*Aut. sim.*	*Aut. diff.*
C	.72	.68	-.04	.39	.75	+.36	.56	.67	+.11	.60	.99	+.39
HYC	.70	.60	-.10	.34	.48	+.14	.45	.55	+.10	.64	.65	+.01
UC	.50	.66	+.16	.31	.37	+.05	.22	.33	+.11	.41	.38	-.03
A	.36	.33	-.03	.50	.32	-.19	1.12	.51	-.61	.49	.35	-.14
HYA	.26	.26	0	.32	.31	-.01	1.38	.33	-1.05	.47	.32	-.14
UA	.49	.33	-.16	.24	.33	+.09	.31	.27	-.04	.27	.28	+.01
N	.41	.68	+.27	.44	.37	-.07	.89	.64	-.25	.67	.50	-.16
NE	.65	.90	+.25	.58	.96	+.38	.82	.41	-.40	.73	.63	-.10
E	.92	1.98	+1.06	.80	.93	+.13	1.22	.55	-.67	.88	.97	+.09
SE	.87	1.38	+.51	.86	1.05	+.19	.76	.52	-.24	1.35	.65	-.70
S	.87	.90	+.03	.58	.46	-.12	1.16	.65	-.51	.33	.69	+.37
SW	.61	.54	-.07	.73	.87	+.13	2.54	3.15	+.61	1.19	1.17	-.03
W	.60	.70	+.09	.71	.82	+.11	1.99	2.11	+.12	.72	1.01	+.29
NW	.37	.53	+.15	.56	.54	-.02	1.26	1.15	-.11	.71	.82	+.10

Table 5.22: Observed (*obs*) and simulated (*sim*) (HadCM2SUL) coefficients of variation, and simulated minus observed difference, of mean seasonal circulation-type frequency over the period 1956-1989 for the Agri.

	Win. Obs.	*Win. sim.*	*Win. diff.*	*Spr. obs.*	*Spr. sim.*	*Spr. diff.*	*Sum. obs.*	*Sum. sim.*	*Sum. diff.*	*Aut. obs.*	*Aut. sim.*	*Aut. diff.*
C	.48	.57	+.09	.35	.45	+.10	.44	.76	+.32	.41	.46	+.05
HYC	.35	.31	-.03	.40	.41	+.01	.50	.49	-.01	.28	.53	+.25
UC	.26	.29	+.03	.35	.31	-.03	.23	.29	+.06	.35	.29	-.06
A	1.31	.52	-.80	.75	.49	-.26	.94	.44	-.50	.82	.44	-.38
HYA	.54	.67	+.14	.60	.54	-.06	1.37	.57	-.80	.52	.49	-.03
UA	.52	.34	-.19	.28	.26	-.03	.17	.23	+.06	.20	.27	+.08
N	.50	.32	-.18	.58	.55	-.03	.30	.45	+.15	.89	.58	-.31
NE	.51	.72	+.22	.91	.77	-.14	.60	.95	+.34	.88	.72	-.16
E	.49	.88	+.40	1.26	1.01	-.26	-	-	-	.85	1.18	+.33
SE	.68	1.09	+.41	.57	.69	+.12	2.37	1.38	-.99	1.09	1.04	-.05
S	.41	.49	+.08	.39	.40	+.01	.98	1.04	+.06	.49	.44	-.06
SW	.46	.58	+.12	.54	.53	-.01	1.63	1.16	-.48	.65	.79	+.13
W	.66	1.08	+.42	.63	.81	+.17	1.44	1.19	-.25	1.05	1.30	+.25
NW	.66	.49	-.18	.49	.73	+.24	.79	.63	-.17	1.08	1.30	+.21

Table 5.23: Observed (*obs*) and simulated (*sim*) (HadCM2SUL) coefficients of variation, and simulated minus observed difference, of mean seasonal circulation-type frequency over the period 1956-1989 for Lesvos.

	Win. obs.	*Win. sim.*	*Win. diff.*	*Spr. obs.*	*Spr. sim.*	*Spr. diff.*	*Sum. obs.*	*Sum. sim.*	*Sum. diff.*	*Aut. obs.*	*Aut. sim.*	*Aut. diff.*
C	.44	.47	+.03	.39	.41	+.02	.33	.81	+.48	.72	.63	-.09
HYC	.48	.54	+.06	.40	.46	+.06	.64	.62	-.02	.67	.71	+.04
UC	.38	.43	+.05	.31	.27	-.04	.37	.28	-.09	.31	.33	+.02
A	.39	.36	-.03	.55	.27	-.28	.67	.34	-.34	.66	.31	-.36
HYA	.46	.29	-.17	.31	.37	+.06	.66	.39	-.26	.49	.31	-.18
UA	.33	.24	-.09	.24	.24	0	.23	.28	+.04	.19	.21	+.02
N	.69	.37	-.33	.77	.54	-.22	1.09	.75	-.34	1.23	.79	-.44
NE	.26	.46	+.20	.43	.58	+.14	.31	.46	+.15	.48	.60	+.12
E	.58	.89	+.31	.62	.81	+.19	.63	.70	+.07	.49	.89	+.40
SE	.94	1.09	+.15	1.25	.77	-.48	4.36	1.82	-2.54	1.42	1.43	+.01
S	.67	.71	+.04	.64	.43	-.21	-	-	-	.72	.65	-.08
SW	.46	.43	-.02	.58	.54	-.03	2.37	1.06	-1.31	.68	.55	-.12
W	1.03	1.01	-.01	.97	.86	-.11	4.36	1.29	-3.07	3.61	1.46	-2.15
NW	1.52	.57	-.94	2.18	.94	-1.24	2.37	.91	-1.46	2.44	1.32	-1.12

Table 5.24: Mean seasonal changes in the frequency (number of days) of the 14 circulation types simulated by HadCM2SUL for the Guadalentin.
Changes which are significant at the 5% (**) or 10% (*) level are indicated (calculated using the Mann Whitney/Wilcoxon rank sum test). Changes which are greater than or equal to the model minus observed differences in Table 5.11 are indicated in bold.

2030-2039 minus 1970-1979

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	-0.4	-2.4*	-1.1	+0.4
HYC	+0.1	+1.2	-0.9	**-1.3**
UC	**+0.2**	-2.2**	-5.4**	-1.2
A	-2.8	+1.8	+0.2	+0.6
HYA	+3.2**	+0.3	+2.6**	-1.6
UA	+1.9	**-3.9***	**+3.6****	**+3.6***
N	**-7.9****	-1.7	+0.3	**-1.8**
NE	-1.3	+1.7	-0.8	-1.3*
E	**+1.0****	**-0.9**	-0.9*	+0.6
SE	**+2.3****	**+0.2**	-0.7	+0.5
S	**+4.4****	+1.8	+0.8	+1.5
SW	+1.4*	0.0	**-0.4***	**+0.9**
W	**-0.2**	**+2.4***	**-0.3***	**-0.7***
NW	**-2.0**	-0.1	**+1.0***	**-1.1**

2090-2099 minus 1970-1979

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	+0.9*	-1.5	+1.3	+0.9
HYC	**+1.9****	-0.2	-0.1	**-0.6**
UC	**+2.8****	-1.4*	+1.2	-0.9
A	**-4.3**	+0.5	-3.0**	+0.1
HYA	-1.0	+2.4*	-1.9*	-1.8*
UA	+1.2	**-4.0****	+0.8	**+3.2***
N	**-11.3****	**-4.4****	-1.0	**-6.0****
NE	-1.8*	+0.3	-1.2	**-2.6****
E	0.0	0.0	+0.5	+0.1
SE	**+1.9****	**+2.2**	+0.3	+1.3
S	**+8.1****	+1.2	+1.9	**+6.3****
SW	**+4.7****	**+1.5**	**-0.6***	+0.6
W	**+0.8**	**+1.3**	**-0.3***	**-0.7***
NW	**-3.8****	+0.3	+0.1	**-0.8**

Table 5.25: Mean seasonal changes in the frequency (number of days) of the 14 circulation types simulated by HadCM2SUL for the Agri.
Changes which are significant at the 5% (**) or 10% (*) level are indicated (calculated using the Mann Whitney/Wilcoxon rank sum test). Changes which are greater than or equal to the model minus observed differences in Table 5.12 are indicated in bold.

2030-2039 minus 1970-1979

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	-4.1*	+1.2	+1.1	-0.4
HYC	**-3.7****	**+1.5**	+0.4	**+0.8**
UC	-0.1	-0.2	+2.2	-1.4
A	**+4.4****	0.0	-1.6	+0.2
HYA	**+4.1****	+0.3	-1.4	+1.0
UA	**+5.1**	-2.8	-0.4	+1.9
N	-0.6	**-3.2****	**-2.4****	-0.5
NE	**-1.7**	+0.3	**-1.4****	**+1.7**
E	-0.6	-0.2	-0.1**	-0.1
SE	+0.4	**-1.1***	-0.5	-0.5
S	**-1.3**	-0.4	+0.8	**-1.9****
SW	**+0.6**	**+0.3**	-0.1	**-1.9****
W	**-1.7**	**+1.5**	-0.1	+0.2
NW	-1.0	**+0.7**	+1.5	-0.2

2090-2099 minus 1970-1979

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	**-6.7****	**+1.7**	0.0	**-1.1**
HYC	**-7.6****	-0.1	-0.3	**-2.0***
UC	**-2.0**	-1.7*	+1.0	+0.2
A	**+5.8****	-0.3	-2.4**	+3.1*
HYA	**+7.7****	+0.2	-1.1	+1.7
UA	-0.4	-0.5	+0.6	+2.1
N	-1.2	**-1.8**	-0.7	-1.3
NE	**-3.1**	+0.2	**+0.4**	**+2.6***
E	-1.1	-0.4	+0.1**	**+0.4**
SE	+3.6**	**+0.3**	-0.1	-1.9*
S	**+1.7**	**-1.5**	+0.9	**-3.1**
SW	**+3.9****	**+0.4**	-0.3	**-1.3**
W	+0.3	**+0.6**	-0.1	-0.1
NW	-0.8	**+0.8**	0.0	**-0.4**

Table 5.26: Mean seasonal changes in the frequency (number of days) of the 14 circulation types simulated by HadCM2SUL for Lesvos.
Changes which are significant at the 5% (**) or 10% (*) level are indicated (calculated using the Mann Whitney/Wilcoxon rank sum test). Changes which are greater than or equal to the model minus observed differences in Table 5.13 are indicated in bold.

2030-2039 minus 1970-1979

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	-1.4	-0.4	-0.3	**-0.7***
HYC	**-3.0***	**-0.9***	**-0.8**	+0.1
UC	-0.1	-0.3	**+5.2****	**+2.7****
A	+2.1	-1.6**	-3.3**	-2.6**
HYA	**+5.7****	-1.3	+0.4	-0.7
UA	+0.6	+0.5	+0.5	**+0.4**
N	0.0	-0.7	+0.6	+0.4
NE	+4.8**	+0.6	-5.0**	-1.1
E	-0.2	+0.2	-1.3	+2.1*
SE	**+0.6****	**-1.0****	-0.2	**-0.4**
S	**-4.3****	+0.3	**+0.6****	-1.5*
SW	**-4.8****	+1.7	+0.8	+0.3
W	+0.1	**+1.7***	+0.5	-0.2
NW	+0.1	-0.9	+0.4	+0.4

2090-2099 minus 1970-1979

Type	*Winter*	*Spring*	*Summer*	*Autumn*
C	**-2.9****	-0.4	**+2.3****	**-1.5****
HYC	**-2.9***	**-0.7**	**+1.2**	-0.4
UC	**-2.1****	-2.0**	**+3.0**	**+2.9***
A	+4.7**	-0.4	**-6.2****	-3.3**
HYA	**+5.0****	-1.7	**-2.3***	**-2.9***
UA	**+0.7**	+0.3	-1.1	**-1.3**
N	+0.7	-0.7*	-0.6*	+0.2
NE	+2.1**	+0.7	-4.4**	+2.5
E	-0.4	+0.8	**+4.2***	+5.4**
SE	-0.2	+0.3	**+0.7***	**-0.9**
S	**-4.0***	-0.3	+0.1*	-1.8**
SW	-1.7	+1.7	+0.5	**-0.7**
W	**+2.2****	+1.0	+0.9*	0.0
NW	-1.1	-0.7	-0.2	**+1.0***